A Variation of Positioning Phase Change Materials (PCMs) Within Building Enclosures and Their Utilization Toward Thermal Performance

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Environmental Design and Planning

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March 21, 2018

Blacksburg, VA

Keywords: Phase Change Materials (PCMs), Thermal Performance, Latent Heat, Thermal Comfort, Load Shifting Time, Positioning, and Building Enclosure

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ABSTRACT

Recently, buildings have been receiving more serious attention to help reduce global energy consumption. At the same time, thermal comfort has become an increasing concern for building occupants. Phase Change Materials (PCMs), which are capable of storing and releasing significant amounts of energy by melting and solidifying at a given temperature, are perceived as a promising opportunity for improving the thermal performance of buildings. This is because they use their thermophysical properties and latent heat while transforming state (or phase) as a feature for thermal energy storage systems to reduce overall energy demand, specifically during peaks hours, as well as to improve thermal comfort in buildings. This research aims to provide an overview of opportunities and challenges for the utilization of PCMs in the Architecture, Engineering, and Construction (AEC) sector, a broader understanding of specifically promising technologies, and a clarification of the effectiveness of different applications in building enclosures design—especially in exterior walls. The research discusses how PCMs can be incorporated within building enclosures effectively to enhance building performance and improve thermal comfort while reducing heating and cooling energy consumption in buildings. The major objectives of the research include studying the properties of PCMs and their potential impact on building construction, clarifying PCMs selection criteria for building application, identifying the effectiveness of utilizing PCMs on saving energy, and evaluating the contribution of utilizing PCMs in building enclosures to thermal comfort. The research uses an exploratory quantitative approach that contains three main stages: 1) a systematic literature review, 2) laboratory experiments, and 3) validation to meet the goal of the research. Finally, by extrapolating results, the research ends with a practical assessment of application opportunities and how to effectively utilize PCMs in exterior walls of buildings.

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GENERAL AUDIENCE ABSTRACT

With the growing concern of energy savings and selecting the most efficient way to provide thermal comfort for buildings' users, buildings need to be constructed with an effective utilization method of materials and systems. Phase Change Materials (PCMs) have the ability to moderate temperatures within a specific range. They can be applied to reduce the energy used in buildings and improve thermal comfort. This is because they absorb heat when materials melt and release it when materials solidify. This research studies the properties of PCMs and their potential impact on building construction and clarifies PCM selection criteria for building applications. Also, the research illustrates the impacts of utilizing PCMs in different positions within an external wall on energy savings and thermal comfort. The research uses an exploratory quantitative approach that contains three main stages: 1) a systematic literature review, 2) laboratory experiments, and 3) validation to meet the goal of the research. Finally, the research ends with a practical assessment of application opportunities and how to effectively utilize PCMs in exterior walls of buildings.

ACKNOWLEDGEMENTS

First and foremost, I praise and acknowledge Allah, the most beneficent and the most merciful, and seek his guidance and forgiveness. Secondly, my humblest gratitude to the Holy Prophet Muhammad (Peace be upon him) whose way of life has provided continuous guidance for me. This thesis appears in its current form due to the assistance of several people. It gives me great pleasure to express my gratitude to all those who have supported me and have contributed in making this thesis possible.

I would like to express my deep and sincere gratitude to:

- My keen advisor and committee chair, *Dr. Georg Reichard*, whose mentorship throughout my research has provided me with a vast amount of knowledge and experience towards pursing my goals. His dynamism, wisdom, vision, sincerity, and motivation have inspired me. I appreciate his support, consistent professional guidance, and friendly continuous encouragement.
- My dissertation committee, *Dr. David Goldsmith*, *Prof. Robert Schubert* and *Prof. Michael Ermann*, for always giving me valuable advice, guidance, and support for this research. I am indebted to them for their insightful thought-provoking questions, constructive criticism, and invaluable assistance they have provided me throughout this dissertation.
- Building Enclosure and Systems Technology Lab (BEST Lab) at Virginia Tech, for allowing me to use their facilities for this research. Thank you, Virginia Tech, for all of the affordances you offered me as well.
- The Ministry of Education in Saudi Arabia and Saudi Arabian Cultural Mission (SACM) in the United State of America, for their support and encouragement.
- Phase Change Energy Solutions (PCES), for their cooperation during this research and for providing me the PCM that I used in the experiments with special thanks to *Dr. Reyad Sawafta* and *Dr. Rami Saeed*.
- SavENRG – RGEES, for their cooperation and for sharing with me the process of selecting, manufacturing, and testing methods of PCMs with special thanks to *Mr. Harshul Gupta*.

I am extremely grateful to my parents for their love, prayers, caring, and sacrifices for educating and preparing me for my future with support and encouragement. No words can express my utmost gratitude to my parents. I ask Allah "My Lord, be merciful to them, as they raised me when I was young." Also, special thanks to my family for their prayers and encouragements.

I am thankful to my wife *Ruba Alhussini* for her patience, understanding, prayers, and continuing support and encouragement. Also, special thanks to my son *Ibrahim* for being patient with my busy lifestyle with hope of a bright future for him. I consider this work to be as much an achievement of theirs as mine.

I express my thanks to my editor *Jessica C. Hajek* for reviewing and editing this dissertation.

Finally, I would like to thank everyone who contributed to this success directly or indirectly whether a community member, a friend, or a colleague.

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1 INTRODUCTION

1.1 OVERVIEW

In historical buildings, structural stability and durability were the main characteristic of well-design building enclosures. Yet, construction practices have continued to change as new equipment is developed, new materials are innovated, and housing requirements change. In the present day, the design and construction of building enclosures must integrate other characteristics that contribute to high performance, such as thermal insulation, heating and cooling load reduction, and the amount of energy consumption. Buildings are designed to create an isolated space from the surrounding environment and provide the desired interior environmental conditions for occupants. The essential role of any building is to meet users' needs and to protect humankind from severe weather. Individual needs vary from person to person and from area to area. This means the requirements in building components in one geographic area do not have to be the same as another area. Therefore, the properties of buildings are different based on locations and must be designed with considerations for climatic conditions that keep the inside spaces cool in summer and warm in winter. Phase Change Materials (PCMs) could provide thermal protection due to their high thermal characteristics that protect indoor environments against heat and cold.

The difference between interior and exterior temperatures in the summer and winter require high-energy consumption. According to the International Energy Agency (IEA), in most countries the average energy consumed by buildings represents 32% of all-inclusive worldwide energy consumption and with approximately 40% of the primary energy consumption in most IEA countries (IEA 2015). The building sector accounts for an even larger portion of total energy consumption in the United States (Ürge-Vorsatz et al. 2015). IEA (2010) mentions that space heating and cooling consumes 34-40% of the total energy use in residential and commercial buildings. Energy usage can be dramatically reduced by improving the efficiency of building enclosure systems and incorporating thermal storage materials into the building enclosure (Zwanzig et al. 2013). Building enclosures affect the way buildings absorb and radiate heat (Baldwin et al. 2015). Efficient equipment and proper building materials in conjunction with the whole building design are considered essential for most building construction in order to improve thermal performance of the buildings (Graham 2016; Raish 2008).

Building materials with high thermal capacity can improve indoor temperatures by 35-45% in comparison to outdoor temperature (even when the building is shaded and unventilated) (Givoni 1994). In some practices, improving the thermal performance is achieved by using thermal mass. For example, in hot arid climates, thermal mass as part of the structural system (e.g., through masonry or concrete materials) can be successfully utilized to absorb thermal energy temporarily during the day and release this energy again throughout the night without transmitting the full amount into the interior space (Meir and Roaf 2002). Also, thermal mass is an essential strategy for indoor climate control in some climates as it can also provide an appropriate solution for protection from intensive weather. However, this may not be practical in cases where different aspects such as wall thickness or weight limitations are of concern, as is the case for off-site construction technologies, and where alternative options for thermal storage can be considered. Therefore, a well-designed building enclosure can play an important role in reducing the energy used to provide thermal comfort for building occupants by improving the thermal performance of the enclosure.

Currently, there is an international focus on the conservation of energy and of natural resources as building materials. As a response, there are three main useful ways to store thermal energy: sensible heat, latent heat, and heat of a reversible thermochemical reaction (Brousseau and Lacroix 1996). For example, timber framed wall systems provide a light-weight solution for off-site construction but typically lack thermal storage capacity. These systems require adding particular building materials to improve their thermal performance. The most commonly used practice for this kind of improvement is adding more insulation to increase the total thermal resistance. PCMs with latent heat storage and capability of storing and releasing a large amount of energy by using a small amount of thermal mass (Sharma et al. 2004) could be used as a confluence area for thermal mass and light weight building materials to improve the thermal performance of building enclosures. This dissertation explores a variation of positioning PCMs within building enclosures and studies the effects of PCM quantities as well as the thickness of insulation on thermal performance.

1.2 Significance of Study

Researching in building materials and the future of their utilization are important for a wide range of researchers and building construction professionals. Most universities and corporations highlight and support research that can improve the construction method and reduce high energy uses in buildings. This research provides alternative approaches for architects, engineers, contractors, and manufacturers of building materials regarding the utilization of PCMs in building construction. Primarily, the research focuses on the differences between PCM utilization in an interior versus an exterior position within a building enclosure, emphasizing its impact on thermal performance. The research introduces an entry point to assess PCM utilization with different layers and different thickness of insulation for hot and cold climates, and it includes proposed selection criteria for building applications.

1.3 Dissertation Structure

Figure (1) presents the general structure of this dissertation.

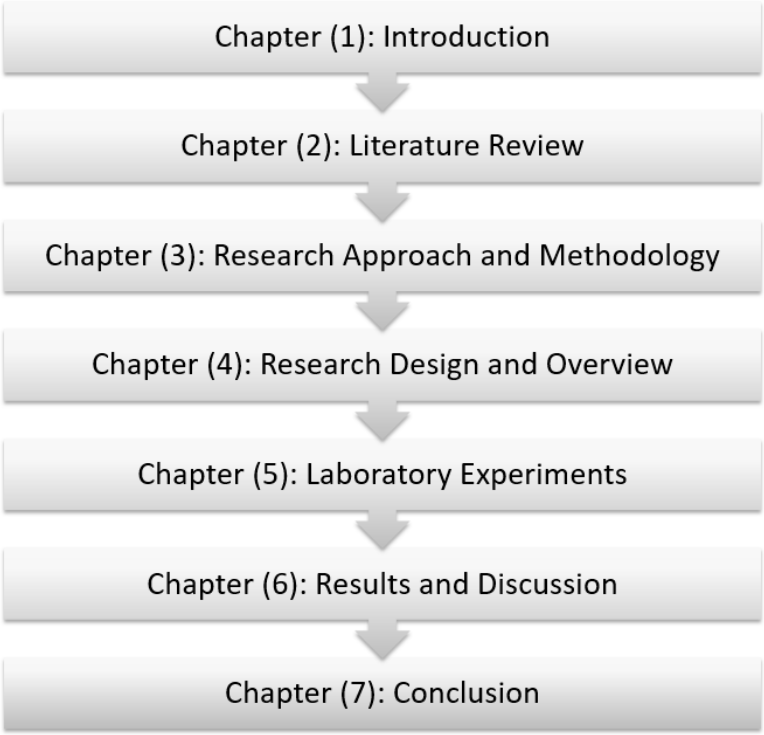


Figure (1) Dissertation general structure.

2 LITERATURE REVIEW

2.1 PHASE CHANG MATERIALS (PCMS) IN GENERAL

PCMs play a major role as thermal energy storage in different successful applications, such as transport and storage containers; clothes for the human body; and packaging for medical and food supplies and electronic equipment. Thermal energy storage allows heat and cold to be stored and used later under two methods: physical methods and chemical methods. According to David et al. (2011), "The principle of the PCM use is simple. As the temperature increases, the material changes phase from solid to liquid. The reaction being endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes phase from liquid to solid. The reaction being exothermic, the PCM desorbs heat" (p. 3117). PCMs have the ability to absorb thermal energy, which means removing or reducing the need for heating and cooling by using sensible and latent heat storage as shown in Figure (2) (Pearson 2010).

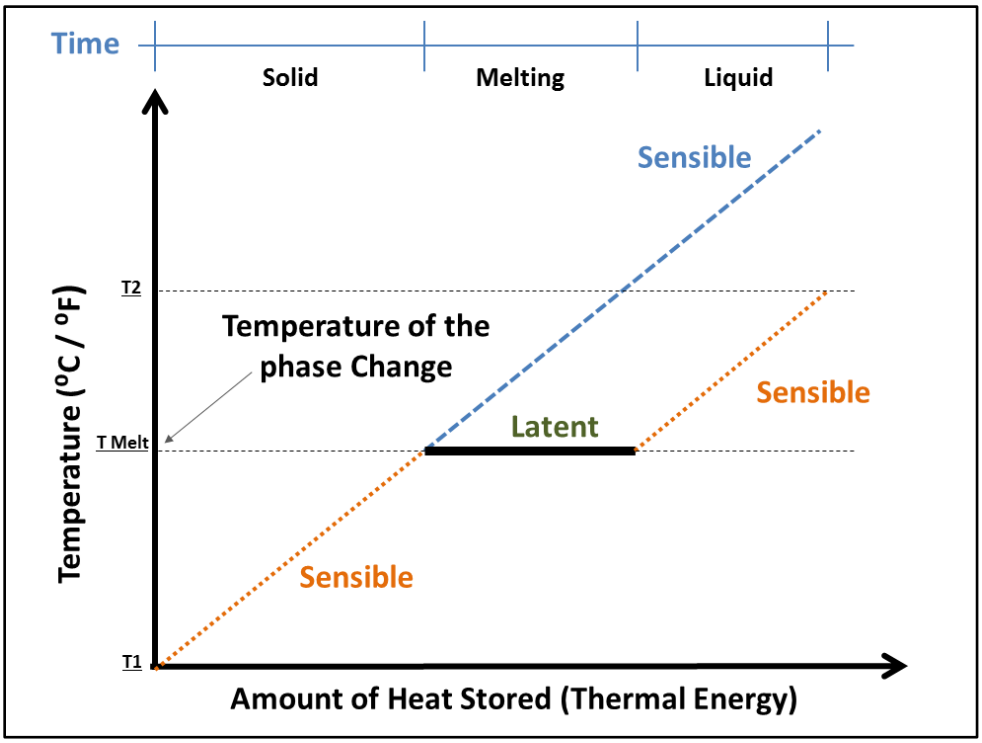


Figure (2) Temperature profile for changing phases by sensible and latent heat. Adapted from (ZAE Bayern 2009).

PCMs are used for different applications and can store and release heat by controlling the required temperatures. Figure (3) shows potential applications of PCMs: Diagram (A) represents different fields for temperature control and Diagram (B) for storage and supply of heat or cold with small temperature changes (Mehling and Cabeza 2008). Along these lines of thinking, PCMs could be used in building construction for temperature regulation, energy conservation, and peak-load shifting to off-peak times/rates and could contribute to thermal comfort in buildings.

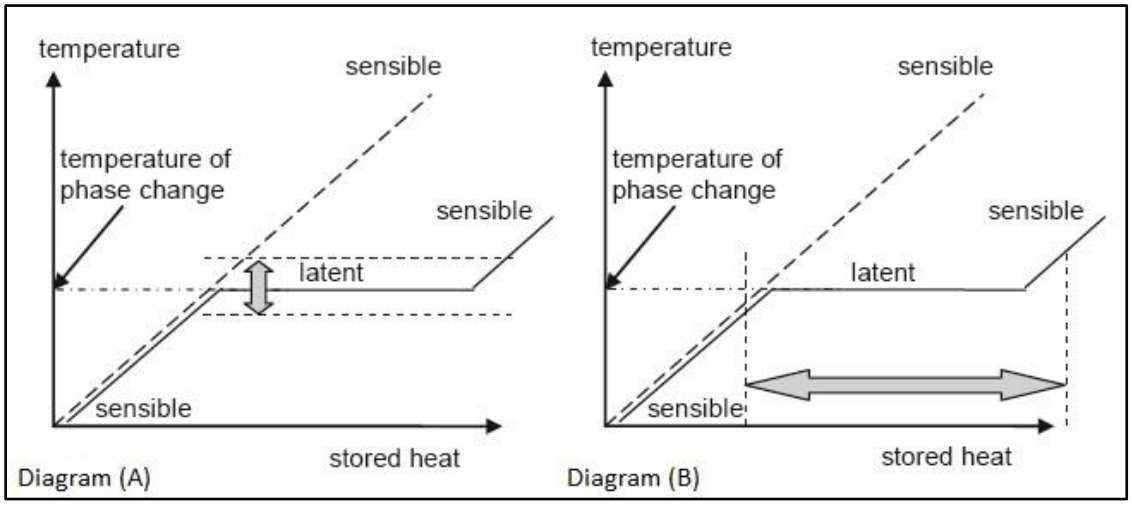


Figure (3) Potential application of PCMs in different fields. Adapted from(Mehling and Cabeza 2008)

2.2 PCM DEFINITION

PCMs are materials that take advantage of a fundamental property of nature – the tendency of materials to absorb heat when they melt (change phase from a solid to a liquid) and to release heat when they solidify (change phase from a liquid to a solid). PCMs as defined by Tyagi and Buddhi (2007) are latent heat storage materials that can be used as a temperature moderator. PCMs are a substance with a high heat of fusion that are able to store and release a large amount of energy when they melt or solidify while more or less staying at this certain temperature until the phase has completely changed (Haghighat 2013; Sharma et al. 2009). As they store and release heat by using chemical bonds, thermal energy transfers occur when the material changes from solid to liquid or vice versa; these processes are called a change in state or phase (Tyagi and Buddhi 2007; Vuceljic 2009).

PCMs can be viewed as a thin-layered version of larger mass walls that can be used to improve the thermal comfort in the interior environment of buildings. They are able to cycle continuously through changes of state both without losing their attributes and by preventing loss in mass through evaporation (Rohles 2007). Figure (4) demonstrates the concept of PCMs' capability of absorbing and releasing heat with repeated melting and freezing cycles, and explains their sensible and latent heat and their effects during cooling and heating (Pazrev 2015).

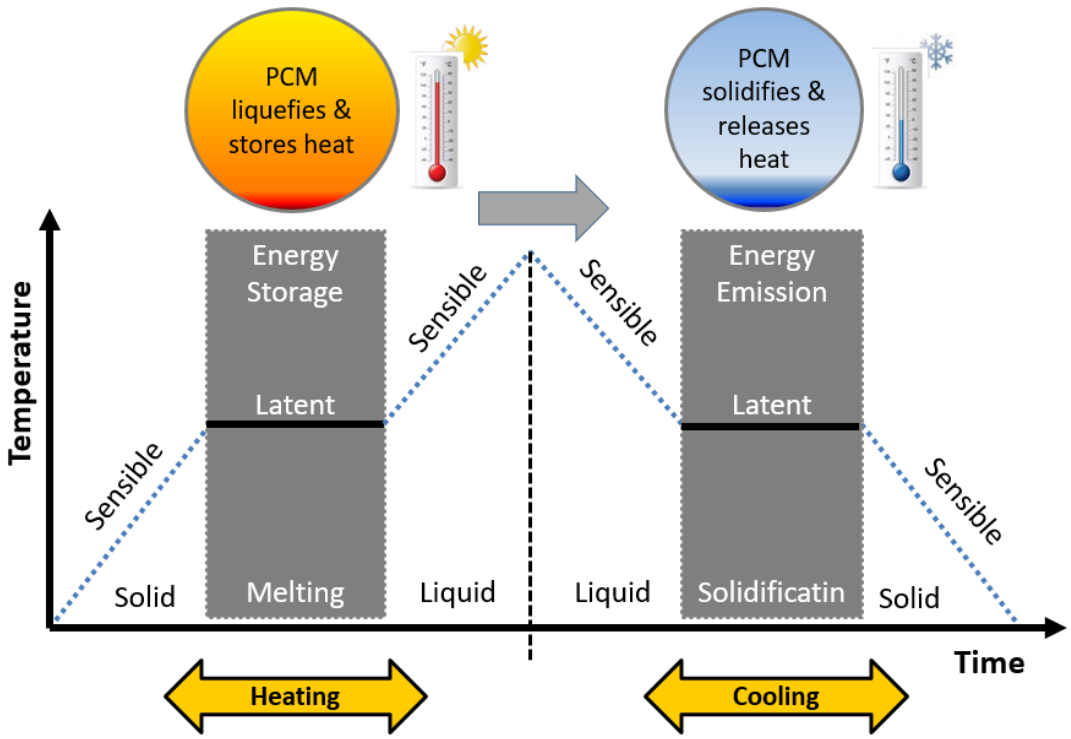


Figure (4) The concept of PCMs' capability of absorbing and releasing heat with repeated melting and freezing cycles. Adapted from (Pazrev 2015).

Latent heating systems have a higher energy density and maintain near-constant temperature throughout the charging and discharging process. Also, cooling and heating have their effects on PCMs. They change the state of the materials from solid to liquid or liquid to solid, and during this process the heat is absorbed or released. Figure (5) shows the effects that cooling and heating have on PCMs (Shim et al. 2001). PCMs could be used in passive buildings by providing a thermal regulation system since they do not require electricity or power of any kind to increase or decrease temperatures in buildings (Microtek Laboratories 2016). Accordingly, cooling and heating could be provided in remote locations without access to electricity.

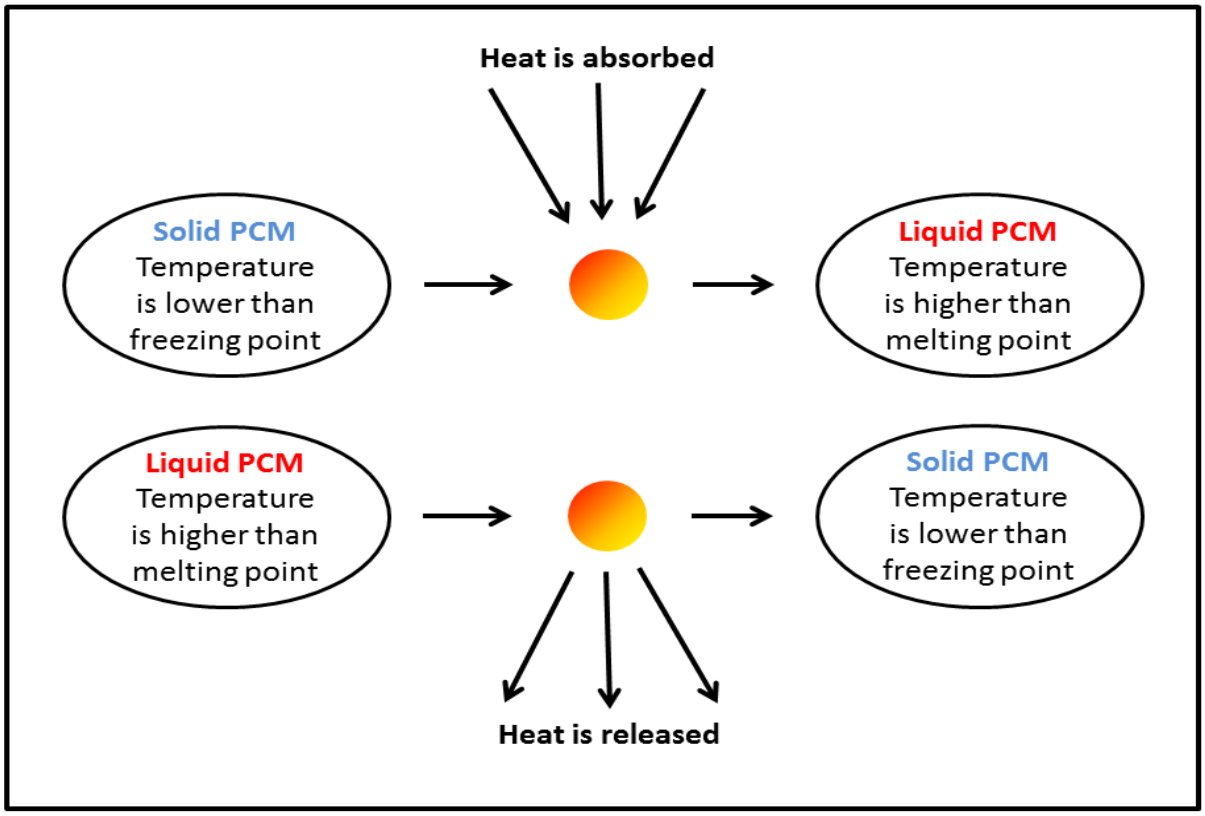


Figure (5) Effects of cooling and heating on PCMs. Adapted from (Shim et al. 2001).

2.3 PCM Properties

PCMs have several properties with a solid-liquid phase transition. Sharma et al. (2009) mention that PCMs have different thermo-physical properties, chemical properties, and kinetic properties. High thermal conductivity, solid and liquid phases, and acceleration time of charging and discharging of energy are examples of PCMs' thermo-physical properties. Sharma et al. also list some examples of chemical properties, such as chemical stability and absence of degradation after a large number of freezing and melting cycles. Nucleation rate, which is beneficial for avoiding super cooling of the liquid phase, is an example of kinetic properties (Ibid.).

The core property of PCMs is based on their latent heat storage capability around their melting points, because large amounts of energy can be stored in a comparatively small volume of PCMs (Madhumathi and Sundarraja 2012). Sharma et al. (2004) list the most common features of the three aforementioned properties of PCMs and highlight the ultimate characteristics of each one (described in the following sections):

2.3.1 Thermo-physical Properties

- Melting temperature in the desired operating temperature range,
- High latent heat of fusion per unit volume so that the required volume of the container to store a given amount of energy is less,
- High specific heat to provide for additional significant sensible heat storage,
- High thermal conductivity of both solid and liquid phases to assist the charging and discharging of energy of the storage systems,
- Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce containment problems, and
- Congruent melting of the phase change material for a constant storage capacity of the material with each freezing/melting cycle.

2.3.2 Chemical Properties

- Chemical stability,
- Complete reversible freeze/melt cycle,
- No degradation after a large number of freeze/melt cycles,
- Non-corrosiveness to the construction materials,
- Non-toxic, non-flammable, and non-explosive materials for safety, and
- Low cost and large-scale availability of the phase change materials is also very important.

2.3.3 Kinetic Properties

- High nucleation rate to avoid super cooling of the liquid phase and
- High rate of crystal growth, so that the system can meet demands of heat recovery from the storage system.

2.4 PCM Types

There is a large number of PCMs that can be classified based on different criteria, such as their melting temperature and latent heat of fusion, the changing of phases, or their source material (Haghighat 2013). Khudhair and Farid (2004a) and Vuceljic (2009) clarify the types of PCMs based on their most common criteria, which is their sources and components. The main sources can be classified into organic compounds, inorganic compounds, and the mixture of two or more components, creating a kind of hybrid type called eutectic, as shown in Figure (6).

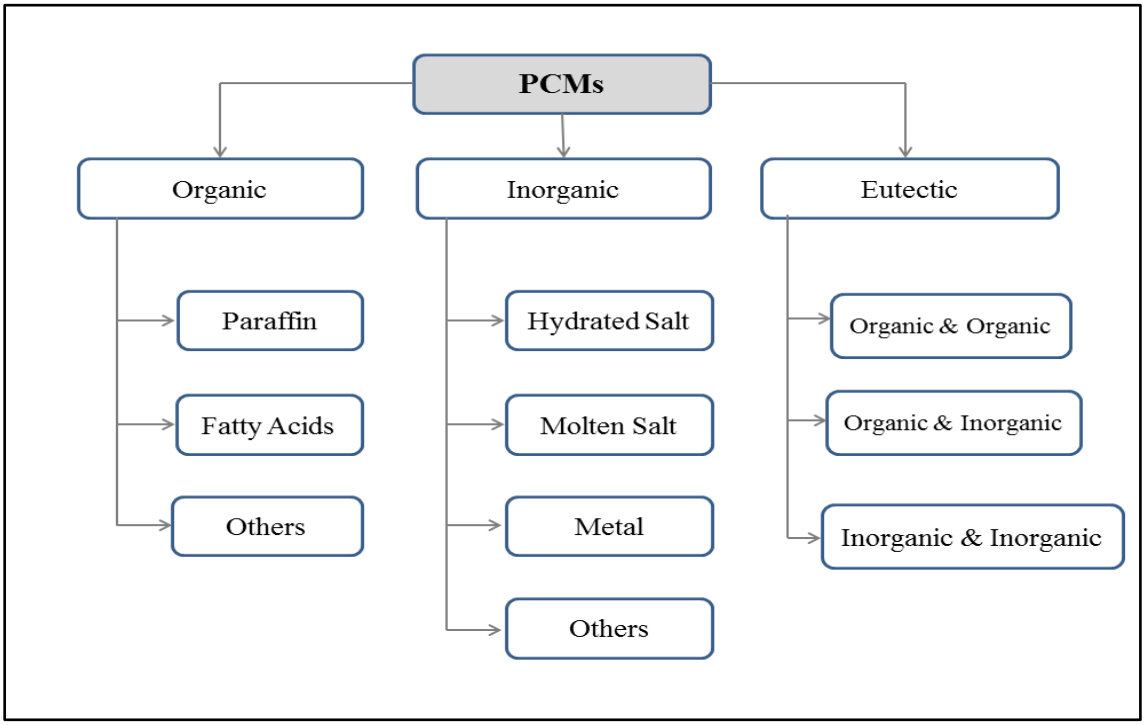


Figure (6) Types of PCMs according to their sources. Adapted from (Khudhair and Farid 2004a; Vuceljic 2009).

2.5 Advantages and Disadvantages of PCM Types

Although organic and inorganic compounds both have high latent heat, which is the most significant feature of PCMs, each type also presents distinct advantages and disadvantages. Organic compounds feature low volume change during phase change, as well as chemical and thermal stability. On the other hand, organic compounds are rarer, have a rather low thermal conductivity, and cost more in comparison with inorganic PCM compounds (Harland et al. 2010).

Moreover, organic PCMs are typically highly flammable, although this can be alleviated in some applications by a proper container (Dubey and Mishra 2014).

Conversely, inorganic compounds have a lower performance of thermal insulation than organic compounds and have rather high thermal conductivity, while at the same time being more affordable (Harland et al. 2010). Some of their main disadvantages are a lack of thermal stability and change of volume after repeated melting and freezing cycles (Mondal 2008).

Eutectic compounds, the third type of PCMs, are a combination of inorganic and organic types and try to capitalize on the advantages of the different base materials, while minimizing the disadvantages. The development of less expensive but highly capable PCMs at a desired temperature, such as fatty acids, is currently being explored (Harland et al. 2010). Also, Harland et al. examined some eutectic products that express more beneficial functions of PCMs—specifically to improve thermal comfort and reduce energy consumption for cooling or heating.

In summary, organic, inorganic, and eutectic PCMs each have their own advantages and disadvantages. Table (1) shows a brief overview of the advantages and disadvantages with some examples of PCMs according to their classification.

Table (1) Advantages and disadvantages of PCMs. Adapted from (Mantz and Wehrle 2015; Mondal 2008; Nath 2012; Sharma et al. 2009).

Types	Advantages	Disadvantages	Examples
Organic	• High latent heat • Non-corrosive • Chemically & thermally stable • Little sub-cooling • Durable and recyclable • Efficient for thermal comfort • High heat of fusion • Low vapor pressure • Safe and non-reactive • Can be microencapsulated	• Not affordable • Low melting enthalpy • Low density • Low thermal conductivity • Rare availability • Flammability (depending on containment) • Volume change • Costly for microencapsulated	• Paraffins (Wax) • Fatty Acids (Oils) • Polyglycols
Inorganic	• High latent heat • High melting enthalpy • High density and latency • High thermal conductivity • High heat of fusion • Sensible heat storage • Non-flammable • Low volume change • Affordable • Very wide melt point range	• Sub-cooling • Corrosion of container materials • Phase separation • Phase segregation • Lack of thermal stability • Instability of volume after repeated change cycles • Loses effectiveness with thermal cycling • Large degree of super-cooling • Cannot be microencapsulated	• Salt hydrates
Eutectic	• Affordable • Sharp melting temperature • High volumetric thermal storage density	• Lack of testing and limited data of thermo-physical properties • Limited temperature range • Corrosive • Cannot be microencapsulated	• Salt water solutions

2.6 PCM APPLICATIONS

2.6.1 PCMS IN DIFFERENT SUCCESSFUL APPLICATIONS

Depending on their utilization, PCMs have the properties of both harvesting energy from solar gains where desired or protecting against solar gains due to their high thermal storage characteristics. Typically, this protection is used during transportation or storage of goods to provide thermal comfort against heat and cold (Prim 2013). Therefore, PCMs have different applications that are currently used to reduce or avoid heat exchange between different temperatures in areas/spaces that need to maintain these properties for different purposes.

There are many applications that benefit from PCMs' useful ability to stabilize temperatures—such as protection of solid food, cooked food, beverages, pharmaceutical products, blood derivatives, hot and cold medical therapies, electronic circuits, clothing, and many other applications yet to be discovered (Prim 2013). More importantly, possible PCM applications include their utilization in refrigerators and freezers that could use less energy, high-performance textiles that could provide relief from hot and cold climate conditions, and shipping containers that could maintain goods at a desired temperature for longer periods.

Currently, the global PCM market is experiencing high growth due to an increasing demand for eco-friendly and energy-saving materials in industries such as thermal energy storage, refrigeration, textiles, and electronics. Table (2) shows an overview of some examples of existing applications of PCMs in different fields (Mantz and Wehrle 2015).

Table (2) Examples of PCMs' applications. Adapted from (Mantz and Wehrle 2015).

Field	Examples of Applications
Consumer Products	Apparel – Shoes – Furniture – Car seats – Automobiles – Lunch and beverage containers – Outdoor gear (sleeping bags, etc.)
Packaging	Medical – Pharmaceutical – Food/produce – Drug testing – Laboratory testing – Chemicals – Biological samples – Vaccines
Bedding	Mattresses – Mattress toppers – Protectors – Pillows – Linens – Quilting – Ticking
Electronics	Computer parts – Handheld devices/phones – Laboratory equipment – Outdoor electronics – Remote telecom stations – Lasers – Military

2.6.2 PCMs Applications in Building Construction

PCMs as latent heat storage materials can be an efficient way of storing thermal energy and are applicable to materials and products that can be used as temperature-moderators in construction and architecture (Vuceljic 2009). The concept of storing heat within a building's walls has been around since at least 1881 (Pacson 2011). The first documented case of a house using a PCM for passive solar heating was done by Dr. Maria Telkes in 1948 (Harland et al. 2010).

Tyagi and Buddhi (2007) mention several forms of bulk encapsulated PCMs that can be used in building construction. These materials provided for active and passive solar applications during the 1980s. In addition, they found that most encapsulated commercial PCM products at that time were inadequate for passively delivering heat to the building after the PCM was melted by direct solar radiation. This can clearly be seen in the building's enclosure, which offers large areas for passive heat transfer. The need for proper building materials with high performance insulation is considered one of the most important building construction applications to improve thermal comfort in buildings (Gracia and Cabeza 2015).

2.6.3 Current Applications of PCMs in Buildings

The uses of PCMs in buildings as thermal storage systems have been of great importance since the second half of the twentieth century (Kośny 2015). The main applications of PCMs in buildings are when spaces are oriented toward the sun and require larger thermal storage units to be used as an insulation layer within wall components. PCMs were traditionally used to provide a comfortable interior building temperature (Vuceljic 2009). More frequently, latent heat storage materials are now used to stabilize interior building temperatures. For example, the application of PCMs in air conditioning systems reduce room temperature fluctuation by lowering the high temperatures from the external daily temperature and reduce home heating and cooling loads by reducing electrical power consumption (Zalba et al. 2004). Also, the use of PCMs to store coolness has been developed for air conditioning applications and reduced energy consumption, where cold temperature is collected and stored from ambient air during the night and is released indoors during the hottest hours of the day (Ibid.).

PCMs are currently utilized with a packaging method in micro- or macro-encapsulated cells for some applications such as interior wall construction that are adjacent to insulation and wallboard, between attic joists, above ceiling panels in a drop ceiling, and floor tiles (James and Delaney

2012). Jaworski and Abeid (2011) reference three existing ways of incorporating PCMs in building structures:

1. Blending PCMs with building materials during the manufacturing process of construction elements such as bricks or plasterboards in wall components,
2. Incorporation of macro-capsules with PCMs in free spaces inside the building such as placing PCMs above suspended ceilings or under floors, and
3. Incorporation of PCMs in parts of furniture or window blinds.

Tyagi and Buddhi (2007) list a number of major applications of PCMs in buildings, which they classified into two different methods for temperature control. The first application deals with passive storage systems, such as PCM trombe walls, PCM wallboards, PCM paints, PCM shutters, PCM building blocks, and air-based heating systems. The second application relates to active storage systems, such as floor heating and ceiling boards. PCMs are used to enhance building performance in many building elements. The following are some examples of current applications:

1. PCM-enhanced solar thermal storage walls,
2. Impregnated concrete blocks and ceramic masonry,
3. PCM-enhanced gypsum board and interior plaster products,
4. PCMs to enhance wall cavity insulation,
5. PCMs to enhance thermal performance of floor and ceiling systems,
6. PCMs utilized in roofs and attics to enhance insulation,
7. PCM-enhanced windows and window attachment products,
8. Use of PCMs for pipe insulation,
9. Use of PCMs for heating, ventilation, and air conditioning (HVAC) systems,
10. Implementing PCMs for fireplace protection, and
11. PCMs to enhance wallboards and insulation foams.

As expected, each of these PCM types have different applications in building construction. Table (3) shows some examples of existing PCM products that are currently used, and lists their location of implementation. Several studies analyze PCMs as energy saving materials due to their flexibility and applicability. PCMs are gaining popularity due to their properties of reduced heat transfer in lightweight materials. The search for capable, efficient, economical, and achievable sources of energy is a continuous attempt carried out by researchers, practitioners, and scientists.

Table (3) Examples of PCMs' applications in building construction. Adapted from (Jaworski and Abeid 2011).

PCM Product	Application
Micro-encapsulated Paraffin Wax	Wallboard
	Ceiling Tiles
	Floor Panel
	Interior Wall Construction
Bio – Based (organic) Materials	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor
Eutectic Salt Mixtures	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor

2.6.4 Motivation for Utilizing PCMs in Building Construction

According to the above introduction and general information about PCMs, the motivation of utilizing them in building construction was revealed—and several aspects encourage implementing PCMs in building practices. Two main avenues have been conducted in this research: 1) to encourage architects, building engineers, contractors, and owners to take advantage of PCMs and 2) to integrate PCMs within building components that are utilized in building construction. These research directions can be described as the following:

1. Effects of PCMs on thermal comfort in buildings
2. Effects of PCMs on energy savings

2.7 Effects of PCMs

In commonly used PCMs, the change of phases from solid to liquid or liquid to solid occurs in the typical temperature range found indoors (20-26°C), which is favorable for building energy consumption purposes (Kolaitis et al. 2013). Therefore, the use of PCMs is desirable for reducing energy consumption because of the discrepancy between the indoor day temperature and the outdoor night temperature (Zalba et al. 2004). Also, they have the potential to improve thermal comfort for building occupants while also having large capacities to store heat and energy in comparison to other materials. For example, PCMs store about three times more energy than water

and six times more energy than concrete for the same wall thickness (Kuznik et al. 2011b). Figure (7) shows the capacity of storable energy for building materials by comparing between seven types of building material that have the same conditions of temperature variation and thickness.

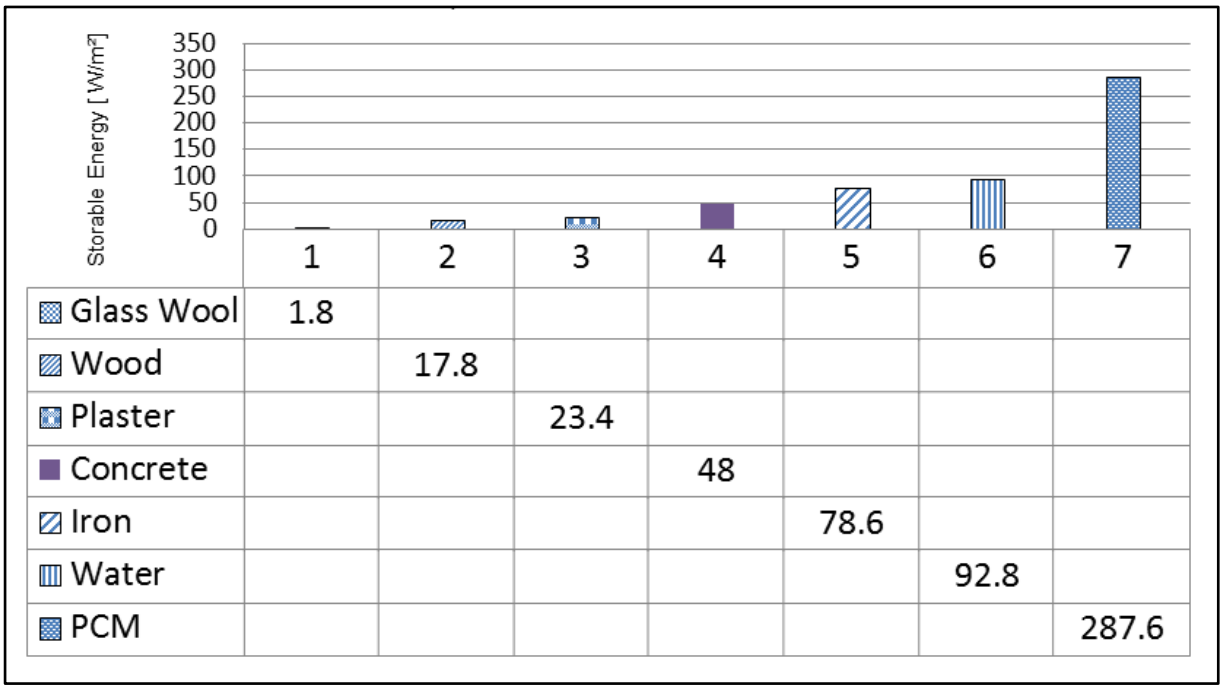


Figure (7) Comparison of the storable energy capacity of building materials under the same conditions of temperature variation and thickness. Adapted from (Kuznik et al. 2011b).

2.7.1 Effects of PCMs on Thermal Comfort in Buildings

Thermal comfort is determined by several physical conditions such as air temperature, relative humidity, airflow, and adjacent wall temperature. Space temperature is considered as an influential factor on space climate and thermal comfort. Building orientation, building materials, occupancy with people, use of equipment, lighting, solar gains through windows, window shading and natural ventilation, thermal mass, and thermal insulation material have a significant impact on thermal comfort. In moderate climates, indoor temperature is recommended to be kept in between 21°C and 26°C with a relative humidity of 30%- 60% (Andersen 2006) as shown in the psychometric chart in Figure (8). This chart represents the thermodynamics properties of moist air and can be used to describe the relationship between dry bulb temperature, wet bulb temperature, humidity, enthalpy, and air density as psychometrics variables (Wujek and Dagostino 2010).

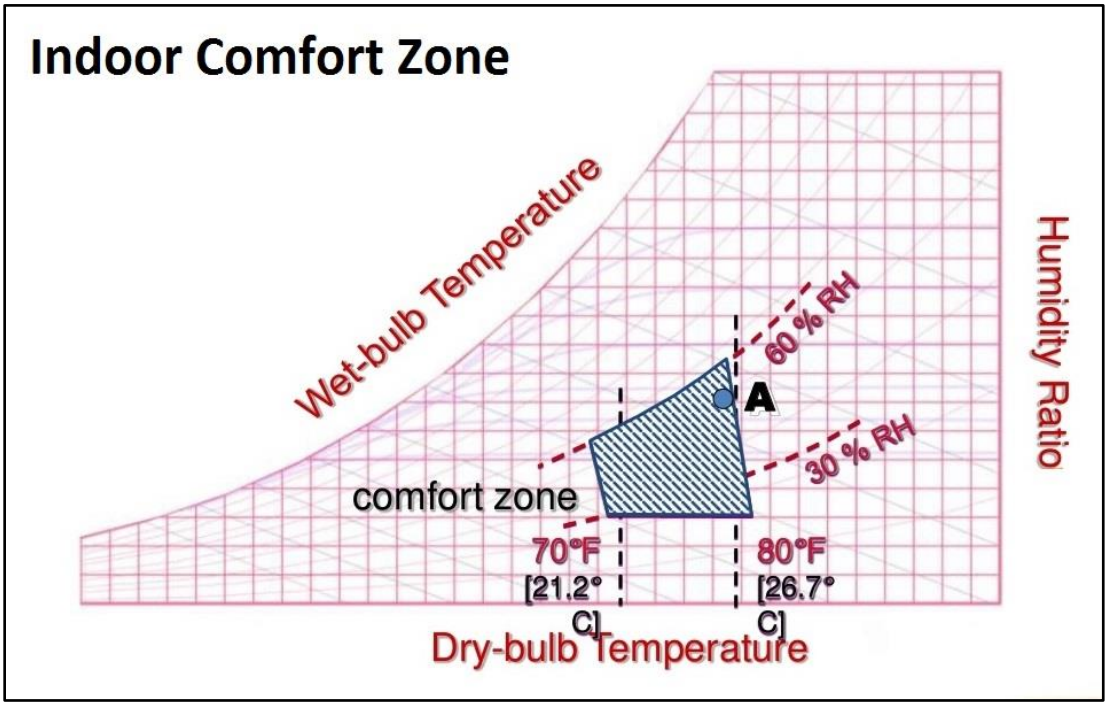


Figure (8) Demonstration of thermal comfort zone through psychometrics. Adapted from (Orange Slides 2014).

Providing thermal comfort in buildings is not only important for improving the living standards or physical comfort demands in terms of heating and cooling, it also plays a major role when considering human performance and/or concentration. PCMs have some features such as thermal energy storage that could be used for improving the internal environment of buildings and creating a notable impact on thermal comfort for building users.

In general, to improve the thermal behavior in buildings, concern for thermal comfort of the occupants and using thermal insulation materials are an essential action to have in order to reduce the thermal amounts of winter heat losses and summer heat gains (Göran Hed 2005; Zalba et al. 2003). Creating a comfortable environment inside most buildings requires a large amount of energy expense and uses a large share of the building's operating cost—although utilizing some building materials could reduce these expenses and improve thermal comfort for occupants. Proper selection of PCMs reduces heat loss in cold weather, keeps out excess heat in hot weather, and helps maintain a comfortable indoor environment without incurring operation costs. Therefore, the use of PCMs in buildings is a possibility for improving higher thermal comfort as it allows the use of latent heat storage to increase the thermal inertia without significantly increasing energy

consumption. PCMs can therefore increase thermal comfort by decreasing the range of internal air temperature differences and providing the desired temperature in the indoor building environment for a longer period (Vuceljic 2009).

Maintaining a stable temperature within the comfort zone for longer periods without relying on HVAC systems may also be possible with PCMs (ClimateTechWiki 2017). Moreover, temperature fluctuations might be reduced, depending on selecting a PCM within the desired melting/freezing point to maintain temperatures within the comfort zone. This will benefit the indoor climate in two ways. First, the temperature will be held more stable by controlling temperature fluctuations throughout the day and will reduce the feelings of thermal discomfort. Second, the peak temperature will be reduced and should never reach a temperature that leads to increased thermal discomfort.

PCMs also maintain a near-constant temperature within the conditioned space while undergoing a phase change. As previously mentioned, they have different applications for building construction, such as insulation products, paint, wall coverings, roofing, solar systems, playing fields, radiant heat, and raised flooring panels. Thus, PCMs as materials and products can be used as temperature-moderators for building construction when they have high thermal conductivity, so that the temperature gradient required for charging the storage material is small and the mass is less than other building materials.

With all the characteristics of PCMs, their application in building construction, the theoretical studies, and demand for high performance products that increase sustainability and livability, a practical assessment of utilizing PCMs in building construction is required to verify their effectiveness on energy saving and thermal comfort in buildings. Such research will also clarify the potential effects of PCMs on thermal performance in general.

2.7.2 Effects of PCMs on Energy Savings

In many countries, cooling and heating of any type of building contributes significantly to overall energy consumption, whose demand is critical when it occurs during peak times (Al-Hadithi 2011). For example, according to the US Department of Energy (2009), in Arizona, 25% of electrical energy consumed in homes is due to air conditioning, which is more than four times the national average. Figure (9) shows the comparison between Arizona and the US overall regarding electrical consumption.

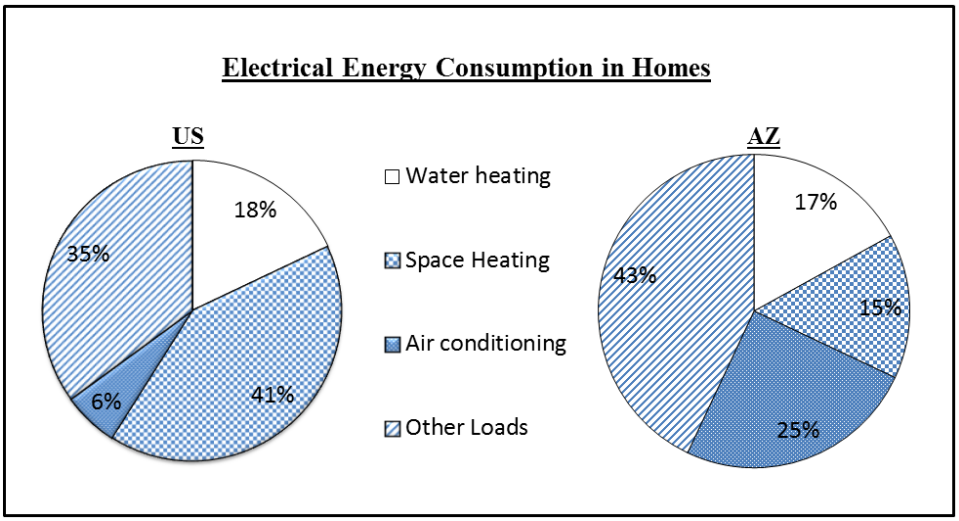


Figure (9) Electrical energy consumption in homes. Adapted from (Energy Information Administration (EIA) 2009).

Over the last decade, the demand for air conditioning has increased greatly and large demands for electric power have led to an increase in efficient energy applications (Vuceljic 2009). Currently, providing electrical energy is often achieved with extra equipment and cost. In building construction, there is a lot of energy savings potential and different methods for possible improvement. One potentially significant impact on energy savings could be achieved by utilizing PCMs in building enclosures as they could either avoid or reduce the use of extra equipment (Zalba et al. 2003). The potential impacts of this are described in the following two sections.

2.7.2.1 Reducing Energy Consumption of Buildings

Heating and cooling consume a large portion of operation costs and vary from building to building and from location to location. PCMs can effectively reduce the dependency on air-conditioning energy consumption per unit area by blocking heat transfer from the outdoors to the interior of the building in climates with periodic temperature swings between day and night (Souayfane et al. 2016). This process could be performed to save air-conditioning energy when applying PCMs in building enclosures. PCMs offer more energy storage capacity and less temperature fluctuation according to their high latent capacity. The effects of reducing the energy needed to run mechanical systems to heat/cool the building can be accomplished by delaying and offsetting the thermal load to the building (Irwin 2015).

PCMs have the potential to reduce radiant heat effects, which emphasizes the ability of PCMs to offset the heating/cooling load by storing incident radiant energy and re-radiating this heat to the exterior when there are temperature swings. In other words, PCMs can reduce the maximum inside temperature and its fluctuations. PCMs can efficiently capture cold energy during the nighttime in summer and reduce the fluctuation of indoor temperature by 4 °C (Shi et al. 2014). In addition, using PCMs in a building equipped with an AC system can result in up to 15% savings in annual energy consumption (Castell et al. 2010).

Using PCMs with high latent heat of melting to increase the thermal energy storage in buildings has been introduced to construction practice to reduce the amount of energy required to heat and cool buildings. This method of storing thermal energy offers higher density of energy storage with a smaller temperature fluctuation compared to traditional methods that use mass as sensible heat storage (Behzadi and Farid 2011). Savings of cooling or heating loads can be achieved by including PCMs in building enclosures, represented by a reduced heat transfer rate and a time lag in the peak indoor temperature. PCMs can manipulate the trend of increased energy consumptions in buildings by combining them with other building materials—in many ways addressing the concern of conservation with minimum expenditure of conventional energy.

Energy consumption in buildings depends on building design, building materials, and the operated environmental context (Harland et al. 2010). For instance, implementing PCMs on building surfaces or within an exterior wall could reduce or at times entirely avoid the need for cooling or heating energy (Sharma et al. 2009). Therefore, the use of PCMs is desirable for improving building thermal performance with the reduction of energy consumption because of their properties, mainly when there is discrepancy between the indoor day temperature and the outdoor night temperature (Zalba et al. 2004).

2.7.2.2 Energy Savings in Total Grid (Network) Consumption

In the US, energy demand that is created by air conditioning can make it difficult for utilities to keep up with the demand during peak periods (Halford and Boehm 2007). Building new power generation facilities is costly and companies are aggressively seeking methods of shifting some of the load away from peak hours to off-peak times. Vuceljic (2009) found that electrical energy consumption varies significantly between day and night and that PCMs can be helpful as building materials because of their high storage density and narrow temperature swings. The author

suggests that encapsulating or embedding suitable PCMs within building enclosures will enhance thermal energy storage, since PCMs can either capture solar energy directly or capture thermal energy through natural convection. PCMs, which change phase during peak times of the day, can play a major role in shifting the high load of demand to the off peak times of day, which allows for purchasing energy at a lower cost (Shi et al. 2014). The thermal storage capacity of PCMs can provide a valuable solution for balancing the supply and demand of electrical energy and shift the peak of energy consumption for HVAC systems to cheaper off-peak hours (Addington and Schodek 2005).

In this load shifting strategy, thermal storage is charged during off-peak times and stores energy in order to use latent heat during times of peak load. It aims to shift the entire peak load to off-peak hours. By decreasing or avoiding air-conditioning operation, electricity consumed during the day is reduced. This strategy is commonly used to take advantage of lower off-peak energy costs and is mostly introduced where on-peak demand charges are high or the on-peak period is short (Valappil 2015). Figure (10) illustrates how the peak might be reduced and the shifting of the peak through the use of PCMs as thermal energy storage, plus the strategies of charging and discharging storage to meet cooling or heating demand during peak hours and shifting the entire load to off-peak hours (Dincer 2002).

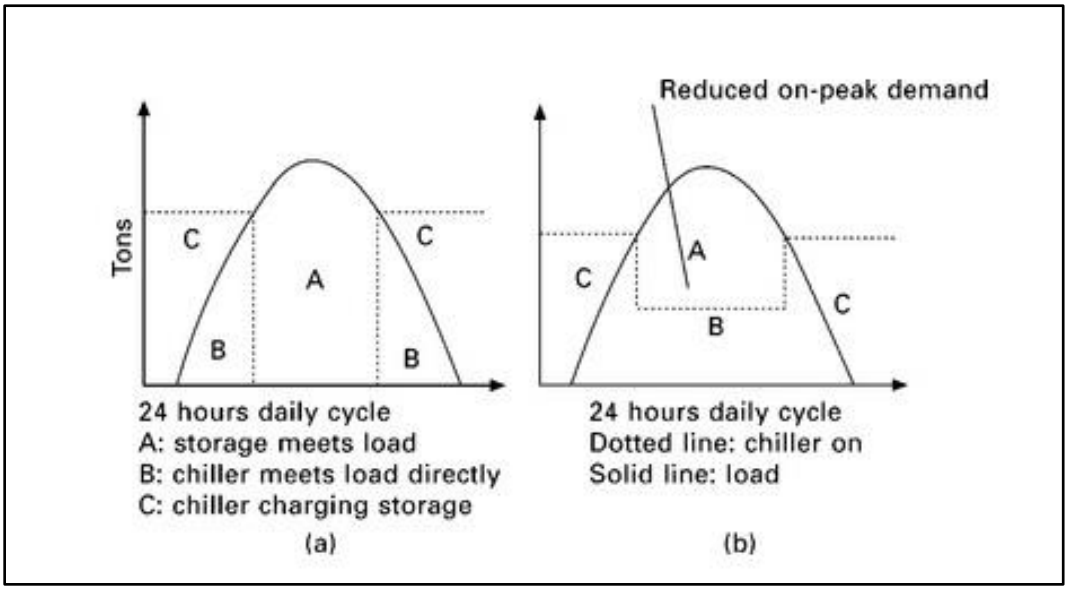


Figure (10) Strategy of shifting the heating or cooling load from peak hours to off-peak hours with thermal storage material. Adapted from (Dincer 2002).

By shifting the peak load away from the peak hours of electrical demand using PCMs, the peak load may be divided throughout the day for reducing the highest peaks (Halford and Boehm 2007). This can lead to a significant reduction of the building's energy consumption by using energy-storing building materials, reducing pressure on the electrical grid, and potentially minimizing the need for HVAC systems for long periods of time. PCMs can also reduce electrical power consumption by lowering high temperatures in comparison to the external daily temperature and reducing heating and cooling loads (Zalba et al. 2004). Furthermore, an appropriate thermal storage material such as PCMs can be used to achieve a significant reduction in equipment cycling frequency and create an observable increase in operating efficiency over traditional building materials (Mehling and Cabeza 2008).

2.8 Current Market and Opportunity

2.8.1 PCMs in the Market

PCMs have been studied for decades and several materials have been considered for building applications to take advantage of PCMs' latent heat capabilities and high storage densities—such as paraffin wax, bio-based organic materials, and eutectic salts. Beginning in 2010, several varieties of different PCMs have been available on the market and the most common forms are paraffin waxes and salts, which can provide a large range of melting temperatures (Harland et al. 2010). Figure (11) shows the global market ratio of the most common type of the PCMs (Transparency Market Research 2015).

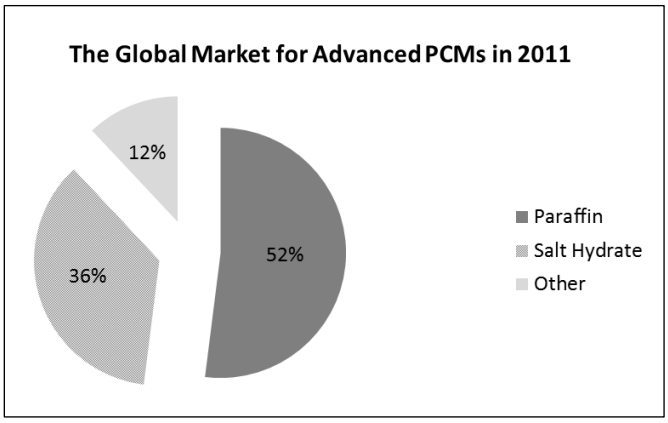


Figure (11) Global market ratio of PCM products in 2011. Adapted from (Transparency Market Research 2015).

Since 2013, the commercial market has had more than 100 varieties of PCMs available at different melting temperatures within the range of 0ºC to 100ºC with latent heat of fusion in the range of 100 to 300 kJ/kg (Milisic 2013). The global PCM industry is experiencing high growth because of increasing applications, technological improvements, and growing concerns of green buildings in accordance with environmental regulations on energy savings (Doshi 2015).

In the immediate future, it is probable that the market for PCMs in construction will become affordable for local-area applications mainly because these resources are becoming cheaper to use and more efficient to apply with conventional methods (Milisic 2013). According to a report from Mordor Intelligence LLP (2016), PCMs were valued at $563.53 million in 2014 and they are expected to reach $1,674.29 million by 2020—representing a compound annual growth rate of 19.9%.

2.8.2 The Opportunity to Utilize PCMs in Building Construction

There is no one best material for all applications and utilizing PCMs in building materials depends on climate parameters and building location, as well as the individual PCM's properties and its actual position within different building components. Climate parameters in a building's location and thermal characteristics of the building not only have an influence on building components themselves, but also on the thermal comfort of the interior space (Al-Hadithi 2011; Fernandes and Costa 2009). Additionally, solar radiation, cloudiness, heat absorption and reflection of the ground, wind speed, and atmospheric pressure all can have a major effect on the indoor comfort environment under natural conditions (Al-Obaidi et al. 2014). Even under these conditions, the opportunity to reduce energy consumption and improve thermal comfort of buildings is obtainable by using PCMs in building construction.

Besides the benefits of reducing electrical energy consumption and improving thermal comfort, utilizing PCMs (with their ability to absorb and store heat) in buildings is being motivated by a desire to implement lightweight materials with less mass volume for passive and active building systems. The building industry is moving toward more lightweight technologies with sensible improvements in manufacturing processes and environmental benefits due to the concurrent reduction of the components' weight and embodied efficient building materials. Unlike traditional thermal mass, such as concrete or adobe, PCMs store similar amounts of heat with significantly less mass.

Using PCMs in such building walls can, therefore, reduce building weight and decrease temperature fluctuations, particularly in cases of solar radiation loads (Kuznik et al. 2011a), and they can be used for thermal storage in conjunction with both passive and active solar storage for heating and cooling (Tyagi and Buddhi 2007). PCMs have a high density, so that a smaller container volume could hold a large amount of the material without causing a chemical reaction with or corrosion of construction materials. The characteristics of PCMs make them more suitable for use in buildings for energy conservation, space-saving implications, reducing building load, and reducing peaks in demand than other thermal storage devices, which require separate systems and more space.

PCMs provide similar functionality for improving the comfort of the interior space in buildings and reducing electrical energy consumption compared to high density materials typically used for thermal storage. However, PCMs now achieve this without the issue of adding significant mass, which can be inappropriate at some levels of construction (Harland et al. 2010). Kosny et al. (2007) state that using PCMs allows for significantly thinner, lighter weight building materials, which are better suited for today's buildings, and that one centimeter of phase-change building materials has the thermal capacity of roughly seven and half centimeters of concrete. Figure (12) compares PCMs with different conventional building materials and shows the necessary thickness to store as much heat as a 1 cm-thick layer of PCM based on certain temperature intervals (Mehling and Cabeza 2008). The use of PCMs in buildings makes it possible to achieve the required space temperature and increase thermal comfort without significantly increasing building weight (Silva and Almeida 2013).

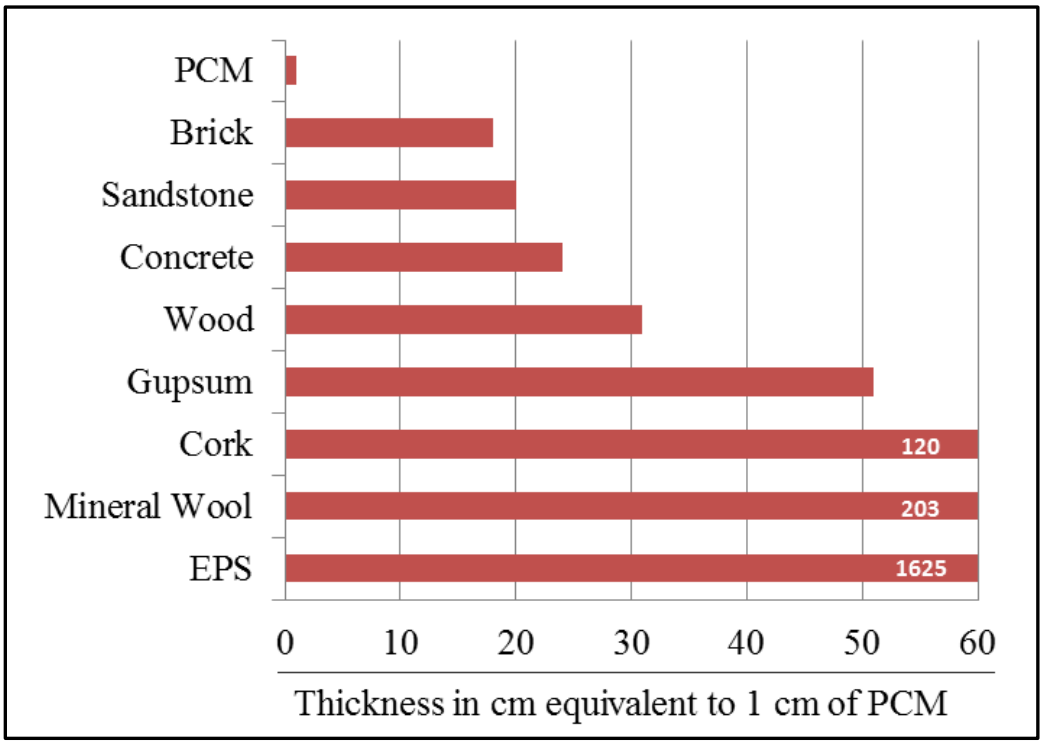


Figure (12) Necessary layer thickness of different building materials to store as much heat as a 1 cm-thick layer of PCM. Adapted from (Mehling and Cabeza 2008).

Moreover, since PCMs do not require a thicker layer of building material as thermal mass to improve thermal comfort for buildings in hot or cold regions, their utilization in building construction adds value through environment conservation as well (Vuceljic 2009). Therefore, they are mostly suitable to be used in lightweight construction because of their impact, which is similar to that on the thermal mass of the building (Pearson 2010).

In addition, PCMs can be used in both new construction and existing buildings; however, some criteria have to be considered when using PCMs in existing buildings, such as sound absorption properties of surfaces or moisture control within enclosure components (Abuzaid and Reichard 2016). When done properly, implementing modified PCM products to existing buildings can improve their performance by increasing their storage mass of heat (Ritter 2007). Bouguerral et al. (2011) emphasize the possibility of using currently-available microencapsulated PCMs, which are made with paraffin waxes embedded in small spheres of polymer, in building construction by mixing them with building materials or facing wallboard. They also found that the PCMs available

on the market can easily be added to plaster and can thus be installed in new construction or during the renovation process of an existing building.

Most of the applications of PCMs in buildings focus on heating or cooling by using natural or manmade resources to achieve the required thermal comfort (Mehling et al. 2002). As previously mentioned, the materials containing PCMs can absorb and release heat more effectively than most traditional building materials, and therefore, they can be successfully used in components of building enclosures to improve thermal comfort in interior spaces (Madhumathi and Sundarraja 2012). Moreover, PCMs can maintain hours of comfort to the interior space while being occupied for longer periods of time (Manioglu and Yilmaz 2008). However, PCMs must be selected and applied very carefully, specifically in accordance with fire and other building codes following sound engineering practices.

Using PCMs in buildings is also suitable to improve thermal comfort because of their ability to adapt to the differences between indoor day temperatures and outdoor night temperatures (Zalba et al. 2004). In hot dry regions, where temperature changes during a 24-hour period are more significant, PCM application becomes an even more motivating factor, as it can reduce and absorb daytime heat gains and improve thermal comfort for interior building environments (Madhumathi and Sundarraja 2012). Thus, PCMs are especially suitable in arid and semi-arid areas, when the solar irradiance is maximal during the day and the energy demand reaches its peaks because of air-conditioning loads (Nath 2012).

In summary, PCMs have the potential to reduce the energy needed for space heating, or cooling, while improving the thermal comfort of interior spaces in building applications as well as reducing the cost during building operation time. Figure (13) shows the potential and the opportunity to utilize PCMs in building construction.

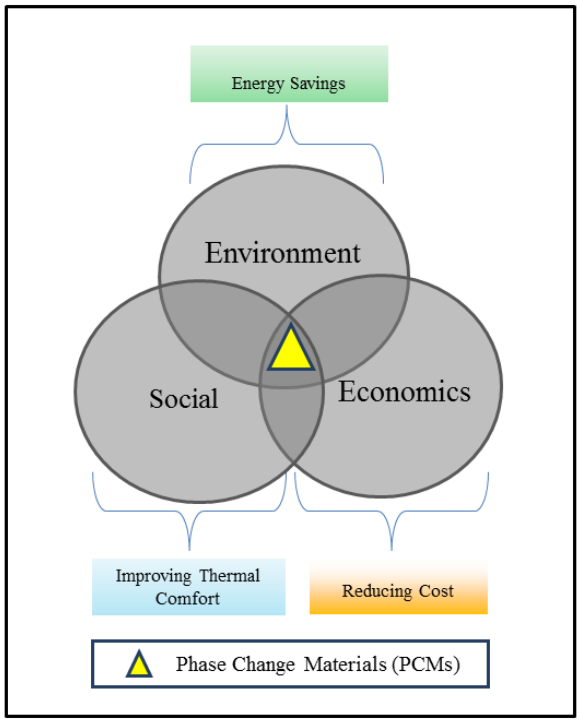


Figure (13) Potential and opportunity to utilize PCMs in building construction.

In general, most lightweight building materials (including PCMs) have the advantages of being energy saving, land saving, waste utilizing, environmentally protective, and increasing labor productivity (Ma et al. 2015). Furthermore, PCMs are useful in reducing transportation time and cost according to their mass and volume. They also require much less labor to install and provide lightweight solutions for achieving up to a 98% reduction in heating and cooling costs of buildings (Craig 2012). Additionally, by taking advantage of PCMs' properties, PCMs help workers and construction laborers to accomplish their tasks with less effort and time in comparison to the quantities of thermal mass of a heavyweight building material. Finally, PCMs are very useful in providing high thermal storage components without increasing building loads, which has a direct impact on the building structure and HVAC load calculations.

2.9 Research Gaps

Background literature indicates the relation that exists between PCMs and their capacity to control temperatures in different applications. Also, it reveals several gaps that exist in terms of utilizing PCMs in building enclosures for energy savings and thermal comfort. These gaps can be summarized as:

1. Gap in technical knowledge,
2. Gap in PCMs selection, and
3. Gap in PCM implementation as building material.

2.9.1 Gap in Technical Knowledge

There is an increasingly empirical and theoretical interest in how knowledge is shared and integrated across building practice boundaries. In building construction practices, theoretical knowledge has a significant role for architects, engineers, contractors, and building material manufacturers. However, a practical application through a scientific approach proves the effectiveness of any building material and shows its improvement to or deterioration in building construction.

Cooperation between scientists, architects, engineers, contractors, and manufacturers allows them to achieve their common goals more effectively in building construction and provides expanded products and materials that can improve building performance. However, PCMs in building construction are still a work in progress in terms of gaps in technical knowledge, research, and effective application. In other words, there is a lack of understanding of PCMs and their application in building construction. The design and engineering community are just now gaining some understanding of the possibilities of PCMs, but the technical knowledge transfer is very slow, especially given the complexity of design for PCMs in building enclosures (Seventh Wave 2016).

While many studies have been conducted to realize the potential benefits of incorporating PCMs into building construction and even though research has increased over the years, there is still a need to conduct more research to enhance the understanding of PCMs and their role in building construction. Figure (14) shows the number of journal articles that have been published between 1979 and 2010 and illustrates the tremendous growth of scientific research over the past few years (Kuznik et al. 2011a).

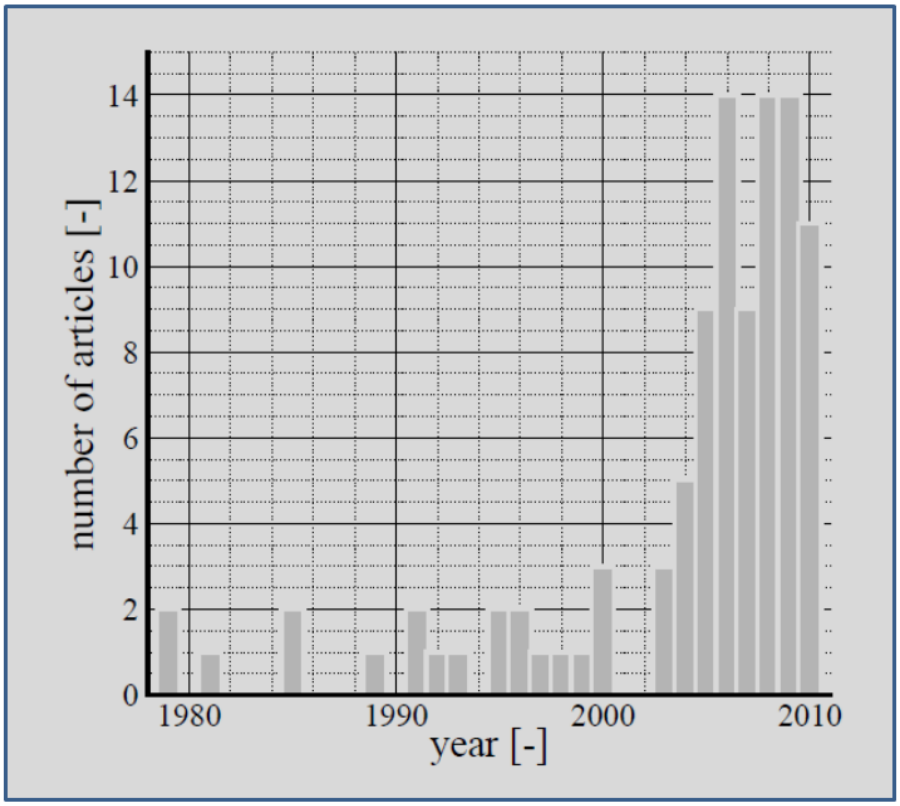


Figure (14) Number of publications of PCMs in building envelopes (1979-2010) (Kuznik et al. 2011a).

In a wide range of building applications, the effect of building discomfort can be solved by air-conditioning systems or by incorporating insulation material in building enclosures. By reviewing the previous studies that focus on different types of PCMs and their application in building construction, this research attempts to fill the gap in lack of knowledge. Concentrating on the studies that use assessment techniques from different perspectives to study varying positioning of PCMs within building enclosures is considered the primary strategy of this research to fill the gap in technical knowledge. The literature review discussed and illustrated the different thermal performance of PCMs, specifically in areas that have a fluctuation in outside temperatures. Quantification of impacts and benefits when measuring the improvement in thermal performance that utilizes PCM can be used to develop a clear understanding of PCMs for building applications. Therefore, a study of PCMs and an evaluation of their uses within building enclosures will enhance the technical knowledge of PCMs and their role in improving the thermal performance of buildings.

In this research, a review of the literature is used to present general information about PCMs such as: their properties, their advantages and disadvantages, their types, and different application. Also, this research highlights the effect of utilizing PCM in building application. The literature review has been carefully delivered to fill the gap in technical knowledge. More specifically, it focused on areas that enhance the understanding of PCMs as latent heat storage materials and their role in building application.

2.9.2 Gap in Selection

There are several factors that need to be considered when selecting a phase change material. The type and amount of PCMs required varies considerably according to building type and location. As previously mentioned, a PCM's temperature remains constant during the phase change, which is useful for keeping the subject or object at a uniform temperature and can improve the comfort level of the environment inside the building when it is used within the building enclosure (Sharma et al. 2009). Thus, selecting a practical solution for building materials has a major role in maintaining thermal comfort and improving building thermal performance in general. For example, in the summertime, peak heat flow crossing a painted roof deck using reflective insulations and PCMs sub-venting air channels was reduced by about 70% compared with the heat flow penetrating a conventional shingle roof (Kosny et al. 2007). This specific application for instance shows the impact that PCMs can have on building performance according to the type of PCM selected, which subsequently affects the thermal comfort of the physical indoor environment (Ibid.). Thus, properly chosen PCMs could improve thermal comfort in buildings and minimize the use of air conditioning systems and energy consumption during warmer and colder months.

Thermal interface materials come in a wide variety of product types and price points. In spite of this, selecting PCMs in building construction remains a challenge task. There is a gap between known and functional applications of PCMs in various fields outside of construction and a potential utilization that is specific for building enclosure systems. Having a basic understanding of their strengths, weaknesses, and applicability is key to the successful selection of the best interface material for application needs.

Ghoneim et al. (1991) mention the required PCM properties for best practices in general applications, which primarily determine the performance of PCMs and include:

1. Melting point should be in the operating temperature range,

2. High latent heat of fusion per unit mass, which ensures high energy density,
3. High specific heat to provide additional significant sensible heat storage effects,
4. High thermal conductivity in both solid and liquid phases, so that the temperature gradients for charging and discharging the storage material are small,
5. Small volume changes during phase transition, as it reduces the size of encapsulating materials and ultimately the heat exchanger,
6. Exhibit little or no super cooling during freezing and possess high density,
7. High chemical stability especially at higher temperatures, no chemical decomposition upon extended cycling, and reaction resistance to encapsulating materials,
8. Should be non-poisonous, non-flammable, and non-explosive elements or compounds in the entire operating temperature range, and
9. Should be affordable and durable.

There is a comprehensive list of possible material that may be used for latent heat storage in different applications (Abhat 1983). Yet, a systematic choice is difficult as a particular PCM may only have some of the desired characteristics but may not possess the others. For example, water has high latent heat of fusion, is cheap and available, and is not toxic, flammable, or corrosive, which make water an ideal PCM. On the other hand, its solid-liquid phase change temperature at 0 °C makes it an unsuitable PCM for any application where ambient temperatures are generally above 0 °C.

Milisic (2013) studied the commercial market and found a large number of varieties of different PCMs that were available at different melting temperatures and different ranges of latent heat of fusion. However, no single PCM has achieved all the required properties, so a suitable system using available materials is required to balance lacking properties with enhancements—such as containment and increasing conductivity (Mehling and Cabeza 2008). In order to fill the gap in selection regarding a suitable PCM for building construction, a systematic review of the literature has been used to highlight the properties that are required in the PCMs to be used in building application. The findings of this review are clarified in this section.

Since the integration of appropriate thermal energy storage systems and the selection of suitable PCMs plays a very dominating role in thermal performance, the selection criteria of PCMs is discussed in this section. There are different types of PCMs for different applications with many purposes (Viljoen et al. 1997). In building construction, not all PCMs can be used as thermal energy storage, as they must have certain desirable thermo-physical, kinetic, chemical, technical,

and economic characteristics (Cui et al. 2015). The literature review included here focuses on the criteria that are related to building applications.

The idea of using a PCM is to store cool energy for day-time cooling requirements in summer or to store heat energy for night-time heating requirements in winter. In order to select a practical qualified solid-liquid phase transition PCM as latent storage material for a specific application in building construction, the systematic literature review below summarizes the essential criteria that were established by Furbo and Svendsen (1977) and further developed by Abhat (1983) and Lane (1983). Recently, Sharma et al. (2009) and Kośny (2015) clarified and emphasized these criteria that are related to the properties of the PCMs for building application as the following:

Thermal Properties for Building Applications: a) The main criteria of selecting PCMs is the melting point, as it must be suitable for and situated in a temperature range between the enclosure boundary conditions to store energy for practical use; b) The heating or cooling temperatures of operation should be matched so that the transition temperature of the PCM is crossed during cycles; c) The latent heat of the PCM material should be high to minimize the physical size of the thermal mass of storage and to be suitable for phase-transition temperatures; and d) Thermal conductivity should be high to assist the charging and discharging cycles of the energy storage.

Chemical Properties for Building Applications: a) The chemical stability during melting or solidifying phases hast to be long-term for suitable building enclosure applications; b) PCMs must be compatible with other building enclosure materials; and c) Any utilized PCM must be nontoxic, nonflammable, non-oxidizing, and non-explosive to be in compliance with fire safety codes.

Physical Properties for Building Applications: a) PCMs should have phase equilibrium and b) PCMs with high density and small volume change are preferable to allow for a smaller size of storage space.

Economical Properties for Building Applications: a) PCMs must be available as a construction material in the regional contexts, and b) They must be affordable enough in a broader context (e.g., initial cost, transportation, construction time) to provide a viable alternative to other construction materials.

While Khudhair and Farid (2004b) demonstrated different properties for building applications, PCMs should have a phase change temperature within the human comfort zone, especially when they are applied close to occupied spaces. Therefore, it is important that the appropriate PCM be

selected for each type of application so that an efficient utilization of a PCM's melting-freezing range is reached and the used latent heat storage can store and release the energy at the desired temperature within a space (Feldman et al. 1995).

These criteria can be considered as an entry point for selecting a practical PCM for building applications—with the optimum melting point varying between 0 °C and 30 °C, depending on application (Whiffen and Riffat 2013). There are significant numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive for several applications. Drake (1987) set up several equations to calculate the optimum melting temperature for a desired PCM. Peippo et al. (1991) further developed these equations to be used as decision tools that contribute to the selection of practical PCMs for a required application. These equations can be used to explain the decision statements of utilizing a PCM in a particular application by calculating the optimum melting point temperature T_m for a PCM (Whiffen and Riffat 2013):

$$\mathbf{T}_{\mathrm{m,0PT}} = \mathbf{T}_{\mathrm{r}} + \frac{\mathbf{Q}}{\mathbf{h} \cdot \mathbf{t}_{\mathbf{stor}}}$$

where T_r is the average room temperature, **Q** is the total heat absorbed per room surface area, h the average heat transfer coefficient between wall surface and surroundings, and t_{stor} the storage time. The average room temperature is calculated through:

$$\mathbf{T}_{\mathbf{r}} = \frac{\mathbf{t}_{\mathrm{d}}\mathbf{T}_{\mathrm{d}} + \mathbf{t}_{\mathrm{n}}\mathbf{T}_{\mathrm{n}}}{\mathbf{t}_{\mathrm{d}} + \mathbf{t}_{\mathrm{n}}}$$

where the different temperatures T and times t are defined by the subscripts d and n referring to day and night.

Barreneche et al. (2014) studied most of the PCMs that can be used for active and passive systems in building applications. They demonstrated a new database to be used when selecting a PCM for thermal energy storage in buildings applications. Also, they showed a different classification of PCMs to be used for building applications according to their melting point. This new database is helpful during the PCM selection process, depending on the requirements of the application. Moreover, Zeng et al. (2017) presented results of evaluable PCMs for building applications and analyzed selection criteria for suitability uses in specific regions. They explained their selection criteria to provide a clear picture of current PCM products with a consideration of changing climate (Zeng et al. 2017).

2.9.3 Gap in Implementation

One of the incentives of using PCMs in building construction is the reduction in storage volume, which can be achieved by using latent heat. This feature allows for saving large amounts of energy better than other heat storage systems (Kaygusuz 1995). In buildings, thermal energy storage comes in two forms: sensible heat storage (SHS) and latent heat storage (LHS). SHS systems charge and discharge energy, or heat, by using the heat capacity of the material and a corresponding change in temperature without changing phase. The SHS capacity of building materials has been recognized and used for centuries by builders to passively store and release thermal energy, but a large volume of building material is required to store the same amount of energy in comparison to latent heat storage. At the same time, increasing the quantity of building material in SHS systems may lead to better thermal mass storage, which can improve thermal comfort without increasing energy consumption, but the structural weight will also increase. Therefore, consideration should be given to materials with low weight and higher heat storage capacity that can also increase thermal comfort and reduce energy consumption. In general, PCMs weigh less and are used in different applications as a temperature moderator, so they could also be used to improve the internal temperatures of buildings while consuming less energy and replicating the thermal mass of a heavyweight building materials in a light building enclosure.

There are different ways to integrate PCMs within building enclosures. Today's constructions increasingly rely on modern lightweight building methods with highly insulating materials. The lack of thermal storage mass leads to a negative impact on indoor climates. The impact of using thermal storage can be seen clearly in thermal comfort and energy savings from cooling and heating. Finding a solution to increase thermal storage without increasing a building's total mass encourages the use of PCMs to achieve the benefits of thermal comfort and energy conservation. Thus, the implementation of PCMs can reduce indoor temperature fluctuations and improve the thermal comfort of occupants.

The most popular PCMs need to be clarified and the practical difficulties in implementing them require a detailed description to illustrate the type and location of each PCM and the best practice of its use in building construction. The thermal improvements in buildings caused by the integration of PCMs depend on the uses of PCMs within different components of the building (e.g., wall, floor, or roof) (Akeiber et al. 2014). There is a large-scale gap in the implementation of efficient thermal energy storage systems and the successful implementation of effective

components in building construction. The appropriate way of integrating PCMs needs to be clarified with information available from the Architecture, Engineering and Construction (AEC) sector based on their vast knowledge of building material behaviors and properties in order to bridge the gap between applicable PCMs and their current use in building construction (Ayyad and Baaziz 2012). Figure (15) shows the gap between AEC decisions and the application of PCMs in building construction, and demonstrates the need to conduct research that involves an assessment of utilizing PCMs in building enclosure systems in order to evaluate the potential improvement in conserving energy and thermal comfort.

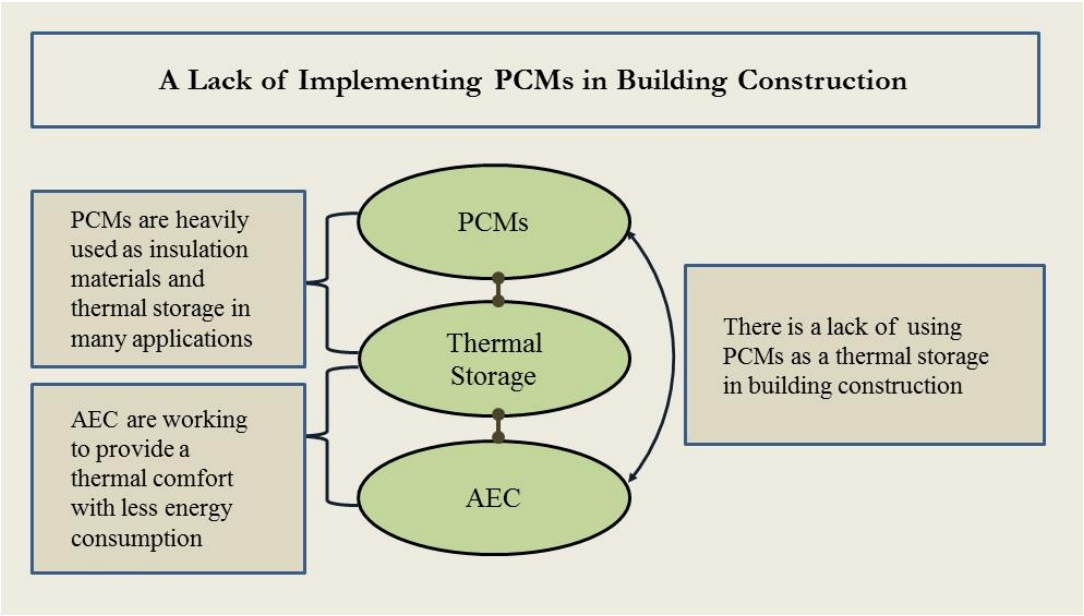


Figure (15) A lack of implementing PCMs in building construction.

A PCM's position within the building enclosure has a significant effect on thermal conditions, and the methods of implementation and positioning need more assessment for best practices in utilization. To fill this gap, a systematic review was undertaken to focus on the implementation of PCMs in building applications. The findings of this review are presented in this section.

For decades, PCMs have been tested as a thermal storage elements in building applications, and the majority of these studies have found that PCMs enhance building energy performance (Kośny et al. 2009). Oak Ridge National Laboratory (ORNL) conducted several experiments to assess the impact of PCMs on building construction. For example, Childs and Stovall (2012) tested selected PCMs placed in an exterior wall and then studied a broad range of parameters that can influence

the uses of a merged thermal storage-thermal insulation system on building performance. Also, Biswas et al. (2013) tested a wall built with PCM and found that an enhanced wall with PCM has the potential for energy savings compared to common cellulose insulation.

Ismail and Castro (1997) conducted field tests for a wall and roof that contained PCM, and demonstrated the effectiveness of PCMs in maintaining a constant and stable indoor temperature and a reduction in the necessary installed capacity of air-conditioning units. Zhang et al. (2005) used a frame wall that integrated a highly crystalline paraffin PCM via macro-encapsulation for field testing. They demonstrated the impact of this enhanced frame wall with PCM on reducing peak air conditioning demand in residential buildings and reducing wall peak heat fluxes by 38%. Mathieu-Potvin and Gosselin (2009) provided a numerical analysis of a wall with one PCM layer to provide fundamental results that may help to understand the impact of a PCM when it is integrated in real building enclosures. Jin et al. (2014) conducted a Differential Scanning Calorimeter (DSC) test for wall experiments, which showed significant effects on the thermal performance of buildings.

In brief, the application of PCMs in building construction has several advantages. The effect varies by the material used and its respective properties as mentioned above, but also changes with different positions. This research illustrates the effects of PCM positions in terms of improving the thermal performance in buildings—specifically in terms of thermal comfort and shifting loads to off peak times. Moreover, thermal performance of any building can be affected by a variety of factors such as the type of the enclosure materials, thickness of insulation, and outdoor conditions (including their period of cooling and heating). Therefore, the effect of PCM positioning within the cavity of a building enclosure on thermal performance was evaluated by using a quantitative comparison method of different wall assemblies and analyzing three positions: a) wall assemblies without PCMs (**NP**), b) wall assemblies with PCMs in the exterior position of a cavity (**EP**), and c) assemblies with PCMs at the interior position of a cavity (**IP**)—with varying numbers of layers, thicknesses, and other components.

Thus, the impact of implementing PCM in building enclosure has been determined and the present study compares three factors to examine their impact on building thermal performance. These factors are:

1) **Impact of PCM position**

To study the impact of PCM position, three types of specimens were investigated: a specimen with PCM positioned on the exterior side of a cavity, a specimen with PCM on the interior side of a cavity, and a specimen without PCM in the cavity.

2) **Impact of PCM quantity**

For this factor, there were two types of components analyzed. First, a specimen with two layers of a packaged PCM layer material were attached to each other to study their effect as a latent heat storage. Second, a specimen with only one layer of the packaged PCM material was studied. Third, a specimen without any PCM was used as a baseline for the comparison tests.

3) **Impact of insulation thickness**

This study used one type of insulation, which was an extruded polystyrene (XPS) with 2.5 cm layer thickness, for a better linear comparison. To study the impact of insulation thickness in connection with PCMs, there were two specimens configured. The first type of specimen utilized three layers of XPS and the second utilized only one layer of XPS.

3 RESEARCH APPROACH AND METHODOLOGY

3.1 PROBLEM STATEMENT

In general, higher standards of living are being demanded today worldwide. This means that air conditioning energy consumption in different seasons represents a challenge in many areas with hot or cold climates. Heating and cooling loads represent the largest portion of energy consumption in buildings. Providing thermal comfort for building occupants is a very important task for architects, engineers, and contractors. PCMs work efficiently in many fields as a temperature controller, but their application in building construction is very rare. PCMs are useful products for thermal management solutions. This is because they store and release thermal energy during the process of melting and freezing—in other words, the change from one phase to another. Yet, high performance PCMs are still not used frequently as thermal storage in building construction and some challenges exist regarding applying PCMs as building materials to be used in the building enclosure. Currently, a lack of technical knowledge of how to utilize PCMs (e.g., positioning and climate) in building enclosures limits the use of PCMs in construction practice. There are several significant potential benefits of integrating PCMs in buildings for improving thermal comfort and reducing energy demand, but further investigations are needed to assess their actual utilization and benefits toward energy performance in building enclosures.

3.2 RESEARCH GOAL

The goal of this research is to provide an overview of opportunities and challenges for the utilization of PCMs in the AEC sector, a broader understanding of specifically promising technologies, and a clarification of the effectiveness of different applications in building enclosure designs—especially for exterior walls. Some secondary goals of this research include:

1. Bridging the technical gap between known and functional applications of PCMs in various fields outside of construction and their potential utilization specific to building enclosure systems.
2. Examining the opportunity of utilizing PCMs in building enclosures to enhance thermal comfort.
3. Evaluating the contribution to energy savings by incorporating PCMs in building enclosures.

3.3 HYPOTHESES

Since PCMs have beneficial applications in several fields, the hypothesis of this research is that the utilization of PCMs as building materials in building enclosures could enhance the following:

1. Improving thermal comfort for a building's occupants by:
    a. Maintaining a more constant indoor surface temperature,
    b. Reducing periods of overheating,
    c. Insulating the interior space from the outside temperature and storing heat to be used later, and
    d. Using a thin layer of PCM that maintains a constant temperature and could be used to control the differences in temperatures across a layer of wall components.
2. Energy savings in buildings by:
    a. Shifting loads to off peak times,
    b. Reducing heating and cooling loads, and
    c. Minimizing running time of HVAC systems and reducing their load.

3.4 RESEARCH QUESTIONS

The following research questions were formulated to address the specific gaps identified from reviewing the current literature. Since the goal of this research is to assess the utilization of PCMs in terms of energy performance in building enclosures based on an in-depth understanding of impacts, benefits, and limitations of integration, the research has been guided by the following overarching question:

How can PCMs be utilized effectively to enhance building performance and improve thermal comfort while reducing heating and cooling energy consumption in buildings?

This question has been further broken down into the following two sub-questions:

- **How can PCMs contribute to energy savings in buildings and what are the mechanisms and systems that can be utilized to achieve these savings?**
- **How can PCMs be utilized in building enclosures to improve thermal comfort and reduce the range of internal air temperature differences?**

The outcomes of this research include developing climate specific empirical models that explain the behavior of PCMs when integrated inside building enclosures. In addition, the climate specific response behavior has been studied to understand the various effects of different variables (e.g., melting temperature, latent heat of fusion, proportion of PCM, positioning within the building enclosure, etc.) in the total thermal performance of a building enclosure. Finally, an effectiveness study has been performed to develop clarification and guidelines that can assist designers and engineers, as well as manufacturers in making performance-based decisions when implementing or manufacturing PCM technologies.

3.5 RESEARCH OBJECTIVES

To achieve the proposed research goal and to answer the research questions raised above, the following research objectives have been laid out. These objectives can be grouped into three main categories and they are discussed in regard to their purpose and context within the overall research goal.

Objective A: Study PCMs' properties and clarify the purpose of utilizing them in building enclosures

This objective discusses three domains:

A.1. Review existing applications of PCMs in different fields and their ability to control thermal temperature

A.2. Study the thermal properties of PCMs that can be used in construction practices

A.3. Review previous studies to understand the impact of utilizing PCMs in buildings on thermal performance

To achieve this objective, first a general literature review has been conducted to study PCMs in building construction, which was followed by a systematic literature review to focus on the application of PCMs in building enclosures. A systematic literature review typically defines an analytical search method based on a set of keywords. The systematic literature review carried out under this objective focuses on keywords such as PCMs, enclosure, energy, comfort, shifting loads, and positioning.

Objective B: Present selection criteria that can be used to choose practical PCMs for building enclosures

This objective discusses three domains:

B.1. Review previous studies that include general properties of PCMs for practical application

B.2. Demonstrate significant properties of PCMs to be used in construction practices

B.3. Determine specific properties and their role when PCMs are utilized in a building

To achieve this objective, first a literature review has been conducted to study the general properties of PCMs. After that, presenting the important properties that have to be considered when selecting a PCM for building construction. Then, a systematic literature review was conducted to specify certain properties and their effects on a building—such as the melting point of a PCM.

Objective C: Evaluate the contribution of utilizing PCMs in building enclosures to thermal comfort

This objective discusses three domains:

C.1. Study thermal comfort and clarify the relationships between utilizing PCMs in building enclosures and improving thermal comfort in a building

C.2. Develop thermal comfort metrics to indicate thermal comfort time during certain periods and measure the differences between configurations in the study

C.3. Evaluate the effect of utilizing PCMs in building enclosures on reducing internal temperature fluctuations

To achieve this objective, laboratory experiments have been conducted. Different climate conditions and different positioning in walls were considered to assess PCMs in different scenarios. For this objective, a PCM was evaluated in a test apparatus under controlled conditions to evaluate the thermal radiant performance of walls with and without PCMs under different temperature conditions. The evaluation includes monitoring of how PCMs behave in different climates, as well as their ability to reduce air temperature fluctuations in a room. Different positions of PCMs within wall components have also been studied to evaluate the relationship between the position PCMs in building enclosures and the thermal comfort of interior spaces.

Objective D: Identify the effectiveness of utilizing PCMs on saving energy

This objective discusses two domains:

D.1. Develop load shifting time metric to indicate period of shifting load to off peak time and measure the differences between configurations in the study

D.2. Evaluate the effect of utilizing PCMs on shifting loads to off peak hours

This objective again has been achieved by laboratory experiments. Different climate conditions and different positioning in walls was considered to assess PCMs in different scenarios. There was an evaluation of the effects of PCMs on energy savings by discussing sensor positions and load shifting time on the exterior versus the interior side of wall components.

Heating and cooling cycles were used to investigate the effects of PCMs on energy savings. In turn, this provided insights into the relationship between the climate condition and the effects of PCMs on reducing a fluctuating range of temperatures for the interior space as well as their impact on time load shifting time. For this objective, assessing an interior and exterior positioning of PCMs in building enclosures in terms of energy efficiency has been achieved using laboratory experiments. Comparing the results identified differences in the potential of PCMs to shift loads to off peak periods and evaluate the contribution of this shifting to overall energy savings.

3.6 Research Methodologies

The study relies on an exploratory quantitative method research design, which includes a systematic literature review, laboratory experiments, and validation. Generally, experimental approach in exploratory quantitative methods contains four elements, which are subjects, materials, procedures, and measures (Creswell 2014) to achieve the research objectives. This approach starts with a systematic literature review and is followed by quantitative laboratory experiments and research validation.

A systematic literature review is necessary to obtain a specific understanding of PCMs, their successful application in different fields, and their potential use in building construction. In the same way, such a review of the literature has also been used to investigate the utilization of PCMs in building construction and provide the required statistical results to prove the benefits of implementing PCMs in building enclosures. The methods described in this research provide a

specific description of the process of PCM behavior during the experimental stage based on the significance of different variables and measurable outcomes.

The systematic literature review has been used both to develop a broad understanding of PCMs under different conditions and to demonstrate impacts of individual scenarios on a larger scale of PCM application. First, data has been collected from previous studies that have similar design conditions. Then, results have been analyzed to evaluate PCMs that can be used for laboratory experiments. The rationale of this approach was to refine and expand results by explaining the existing technical knowledge, as well as providing a broad picture of the opportunities and challenges for the utilization of PCMs in the AEC sector. Both data sets have been merged into one final output to provide better understanding of specifically promising technologies and applications in building enclosure design.

In this exploratory quantitative method approach, a systematic literature review has been used to understand PCMs and their role in building application in the theoretical stage, and laboratory experiments were conducted to collect quantitative data in the practical stage. In summary, to achieve the objectives of this research, three main approaches have been used in this research:

1. Systematic Literature Review
2. Laboratory Experiments
3. Validations

By using an exploratory quantitative approach, the goal of the research has been achieved to end with a practical assessment of application opportunities on how to effectively utilize PCMs in exterior walls of buildings as a way to enhance building performance and improve thermal comfort while saving energy.

3.6.1 Systematic Literature Review

A systematic literature review is a methodology that identifies relevant studies, considers their quality, and provides a brief synopsis of their results by using a scientific examination of the information that is available on a given topic (Khan 2011). To this end, Khan (2011) lists the five preferred steps in a systematic review. These steps are: 1) Framing questions for a review; 2) Identifying relevant literature; 3) Assessing the quality of the literature; 4) Summarizing the related information; and 5) Interpreting the findings.

The systematic literature review methodology uses an approach that selects only specific studies that meet particular criteria, meaning the studies that particularly emphasize the reliability of the evidence that is produced by a previously published research (Ham-Baloyi and Jordan 2015). More specifically, it uses a precise set of criteria by which one considers the precision and validity of previously published research as the primary feature of a systematic review (Ibid.).

A systematic literature review methodology has been used in this research to narrow down the list of relevant variables that have a significant impact on energy savings and thermal comfort to develop a guideline and experimental setup. The researcher started by specifying the research questions to conduct research on PCMs in general and for different applications in different disciplines. Then, a set of keywords was defined and used to determine the analytical research method in relevant studies. This step was followed by studying PCMs in building construction and their uses for different climates. After that, PCMs' applications, particularly in building enclosures were considered by focusing on their impact on thermal performance. Finally, this method was used to summarize the criteria for selecting PCMs for building construction and to select a PCM that would be used in this research. Figure (16) shows the main steps of the systematic literature review in the research.

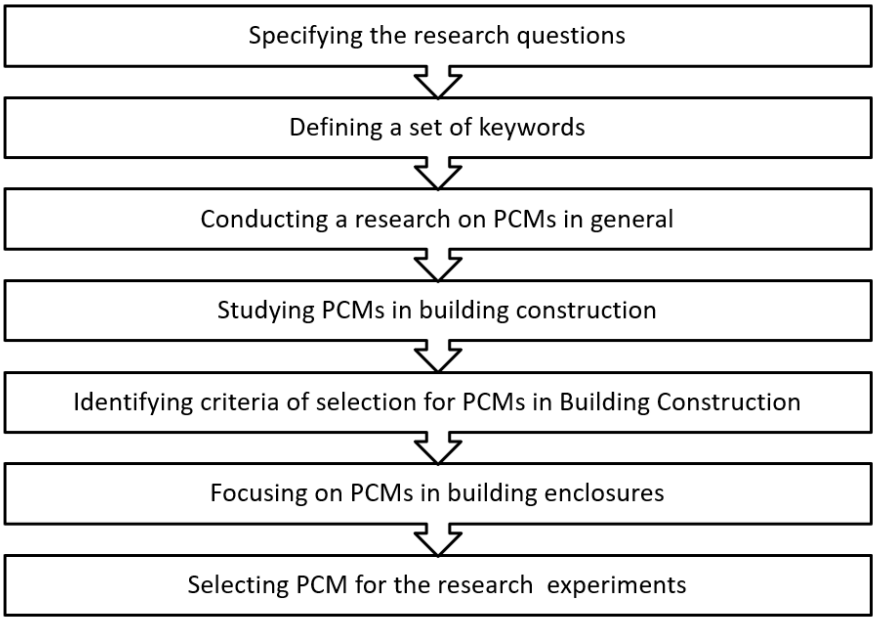


Figure (16) Steps of the systematic literature review.

3.6.2 Laboratory Experiments

An experiment is a test of a hypothesis to study the actual relationship between two or more variables (Patzer 1996). The purpose of an experiment is to study a cause and its effect(s) to define the possibility of uses and implementations. This differs from non-experimental methods in that it involves the deliberate manipulation of one variable, while trying to keep all other variables constant (Holah 2006). The experimental method is one of the most scientific methods, and experimental research can be described as the cornerstone of a research study due to the main role that experiments play in many science domains (Ibid.). The experimental method could be described as a systematic and scientific approach to investigating different variables by controlling one or more variables as a means to observe and measure any change in other variables.

Typically, the laboratory experiment is conducted in a setting expressly prepared for the research study and two main features: 1) the ability to investigate an actual causal relationship and 2) the possibility to control a major component of the research study (Patzer 1996). It is important to keep in mind that this methodology is typically carried out in artificial environments with specific control over individual variables.

3.6.2.1 Lab Experiments in building construction

Laboratory experiments are very common in building construction because they allow researchers more control over involved variables and they are easier to validate the results. The main advantage of this methodology is the possibility of replicability and studying under a controlled environment; however, at the same time this is a drawback as it only validates results of an artificiality setting. Laboratory experiments are widely used to study many types of materials and often test a product later in the actual environment (Holah 2006).

3.6.2.2 Experiments in regard to thermal performance: comfort and energy

Thermal performance has been studied in experiments for decades. In 1978, Hannay, Laret, Lebrun, Marret, and Nusgens studied experimentally the thermal comfort of a room heated by different producers, such as a radiator, a convector, and a heated floor (Le Dréau et al. 2014). In 1980, Olesen et al. conducted an experimental study for thermal comfort as a part of a larger research project dealing with the comparison of thermal comfort and energy consumption in a room heated by different methods. The purpose of such studies has primarily been to determine

thermal performance and the parameters that could affect it in different disciplines. For example, Lawal and Ojo (2011) assessed thermal performance of residential buildings in field experiments, whereas Peng et al. (2013) conducted an experiment research to study the thermal performance of a novel photovoltaic double-skin façade.

3.6.2.3 Experiments with PCMs in construction

Scientists and researchers have been experimenting with PCMs for construction applications in different ways. In several studies, specific experimental conditions were designed to study PCMs. For example, Lin et al. (2005) studied under-floor electric heating systems with shape-stabilized PCM plates in a prototype house. Different PCMs were studied with different melting and solidification processes that were then experimentally tested in the field and laboratory (on a larger scale) in a shell-and-tube heat exchanger for various inlet temperatures and mass flow rates. More pertinent to this study, Zastawna-Rumin and Nowak (2015) analyzed thermal performance of building components that contained PCMs in experimental study.

3.6.2.4 Experimental context for research application

In this research, laboratory experiments have been conducted to achieve objectives C and D, which require a real experiment to fulfill the actual aim of this study. Moreover, experiments were carried out under these sections to demonstrate the cause and effect within the experimental setting and control of variables.

3.6.3 Validation

There are several methods to validate the results of experimental research. The main two types are internal validations and external validations. Experimental research is the most appropriate study for drawing relationship between cause and effects, and most experimental research designs are repeatable and therefore, results can be checked and verified internally (Center for Innovation in Research and Teaching (CIRT) 2010). In laboratory experimental research, better results are often achieved according to the controlled environment, and experimental research designs help to ensure internal validity (Ibid.). Also, the experimental procedure and method of conducting testing are the main parts of the internal validation (Creswell 2014). Therefore, to validate the results of the laboratory experiments, an internal validation strategy has been used. Different input factors and different climate scenarios have been demonstrated to realize the validation strategy through

verifying the opportunity to utilize of PCMs in building enclosures, and especially in wall systems. Validating the results of the laboratory experiments used internal validations through:

1. Repeatability of the same experiment for the same specimen for three days with two cycles of cooling and heating for each day with the same parameters to verify the result of the tests. The repeatability has been used for all test configurations.
2. Sequential testing to validate consistency in conditions of the experiments, to compare different specimens that have faced the same condition, and to demonstrate the similarities and differences in each test result.

3.7 Capturing Objective Data and Measurements Methods

Various measurement methods and setups can support thermal performance assessment but capturing objective data and numerical outputs for assessing the influence of PCMs on thermal performance is dependent on the measurements, equipment, and properties of the materials. Commonly, theoretical and experimental analyses of a building's thermal performance can be conducted on three levels: material scale, system scale, and entire building scale (Fletcher et al. 2015). However, in laboratory experiments, the assessment of PCMs and their effect on the thermal performance of a building is usually limited to an analysis of the material and systems scale. Since PCMs have complicated thermo-physical properties, different measurements, and several characterizations when they change phases, defining their thermal characterization is essential for assessing their impact on thermal performance. Moreover, doing so provides reliable data for assessments. Also, the most conventional equipment and methods are commonly designed to test solid or liquid materials with a steady state temperature. Alternatively, some techniques are designed to test small, pure, and standardized materials, which do not undergo changes in properties during temperature change—such as sub-cooling and significant variation of the thermal conductivity.

However, nowadays, there are particular technologies that are available for measuring the thermo-physical characterization of PCMs, specifically latent heat of fusion, melting/freezing temperature, enthalpy temperature, and thermal conductivity and diffusivity of the materials. Most of these measurement techniques and equipment have been developed in different research centers and universities to analyze thermo-physical properties of PCMs. These measurement techniques include, for example, Differential Scanning Calorimetry (DSC), the Twin bath method, T-history method, T–t comparative curves (Kośny 2015), Panel test experimental set-up, Simple thermal

analyzer, Thermal test device, Energy balance setup, PCM-air heat exchangers set-up, Test room from Fraunhofer (Cabeza et al. 2015), and wall simulators (Evers et al. 2010).

The most commonly used and widely accepted techniques to determine the properties of PCMs and how they react according to temperature change are: the Differential Scanning Calorimetry (DSC), Differential Thermal Analysis (DTA), the T-history Method, Dynamic Hot-Box Testing Method (DHBTM) (Cabeza et al. 2015; Kośny 2015), and wall simulators for different structural systems in test apparatuses and chambers (Vicente and Silva 2014). This research uses an experimental wall simulator (EWS) with thermocouple sensors in every layer of the specimens to record data the method to capture the objective data. Figure (17) shows a screen shot of the raw data recording during experimental time.

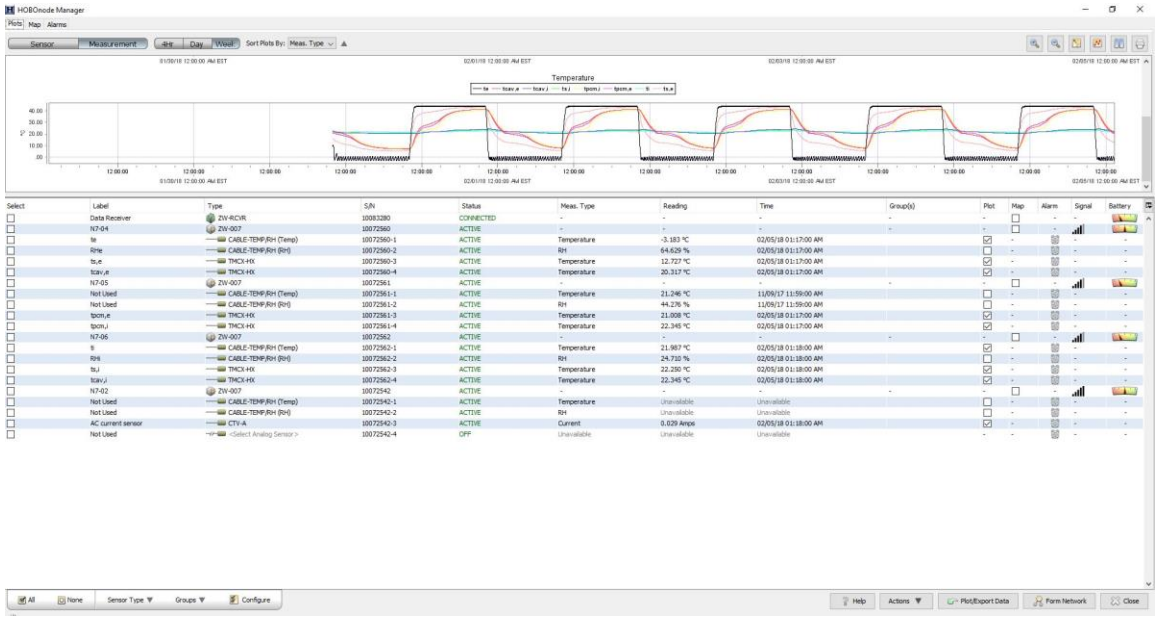


Figure (17) A screen shot of recording raw data by HOBOware software.

3.8 EXPERIMENTAL WALL SIMULATOR (EWS)

This method has been used for many experiments and research studies. It was developed to measure heat transfer through building enclosure assemblies and study the impact of PCMs on different evaluated factors. It has two main parts: 1) A 5.0 cu ft chest-freezer to be used as a climate cell for the test apparatus to simulate different weather scenarios by replicating cold exterior temperatures, and three light bulbs (40 watts each) to create the hot exterior temperatures within

the chest for comparison and 2) Wall specimens with different configurations (component and thickness) to simulate a common wood framed stud wall with cavities.

The EWS method has been used to assess the effects of different PCM specimens in different positions on thermal performance of building enclosure components. The benefit is EWS is that it is capable of changing the external temperatures and controlling the exterior space for certain time. It is therefore used to test the thermal performance of non-homogenous specimens, such as complex wall assemblies, cavity walls, insulated walls, or walls with PCMs. This is done by controlling the temperature on the exterior side of the material and measuring internal temperature fluctuation, which can be used to determine the thermal transmittance of a similar material as well as different materials for tested specimens. This research used EWS for testing different types of specimens in the laboratory experiments as a means to assess the influence of PCMs on thermal performance. A detailed description of its features and components are discussed in the experimental setup.

3.9 Dependent and Independent Variables in the Experiments

This research focuses on studying a PCM in different positions within an enclosure assembly as well as investigating the practical methods of implementing PCMs for different climate temperatures. This has resulted in tangible benefits, emphasizing the features of utilizing PCMs in building enclosures by conducting practical experiments and illustrating the effect of a PCM's position on thermal performance. Also, these experiments clarify how the method of utilizing PCMs can play a major role in reserving energy and improving thermal comfort for building occupants.

Several variables have a significant impact on the assessment process and these variables are divided into two groups: 1) dependent variables and 2) independent variables. The group of dependent variables incudes thermal comfort, load shifting time, and PCM behavior, and the group of independent variables includes PCM position, PCM quantity, thickness of insulation, heating and cooling time, and exterior and interior temperatures as shown in Figure (18). Consequently, this research shows the variations of PCM positioning and their impact on thermal performance according to the dependent measurable variables.

The laboratory experiments have a replicability feature, which supports the results and clarifies the practical implementation method of PCMs. More specifically, by running hot and cold climate

scenarios and changing the position of a PCM layer in a building enclosure, the fluctuation of the interior temperature was perceptible. Therefore, the laboratory experiments allow the specific effects of independent variables on dependent variables to be measured. This makes it possible to establish cause and effect relationships between variables. Moreover, the controlled conditions of laboratory experiments allow the researcher to isolate variables more effectively than with any other research method. This further allows the researcher to accurately measure the exact effect that other independent variables have on the dependent variable.

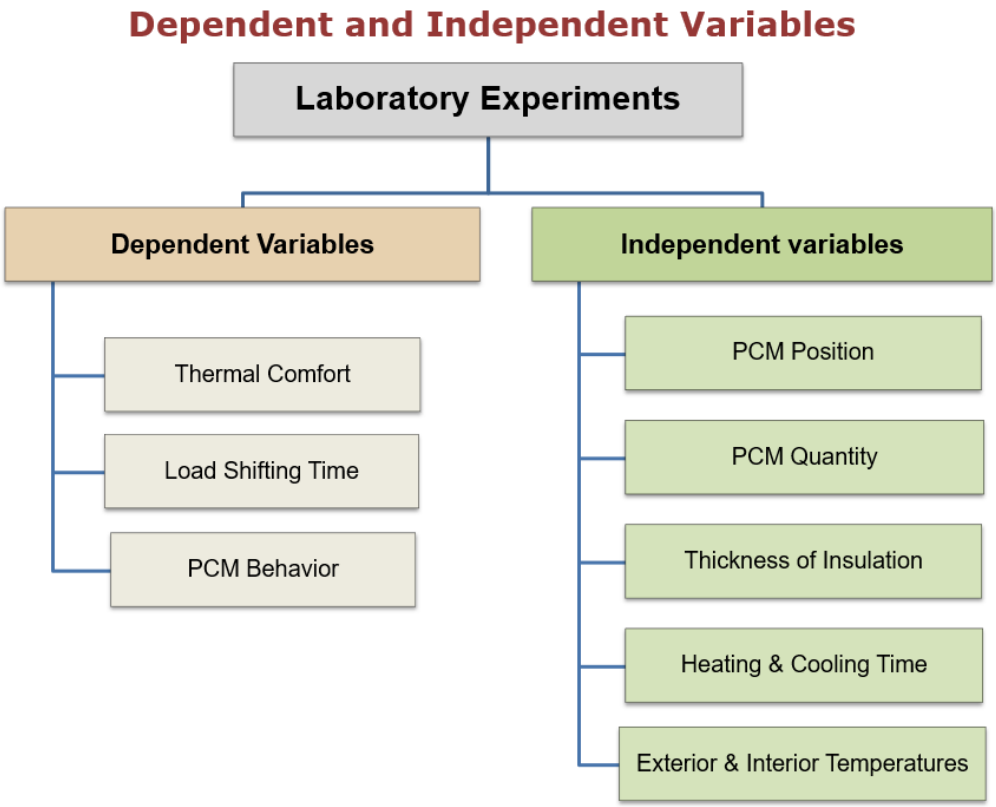


Figure (18) Dependent and independent variables in the laboratory experiments.

3.10 Evaluation Criteria to Characterize the Influence of PCMs

The evaluation criteria in this research are divided into two main groups to characterize the influence of PCMs. These groups are: 1) evaluation criteria to characterize a PCM's influence on thermal comfort and 2) evaluation criteria to characterize a PCM's influence on energy savings. Working on these two factors is very important for evaluating a PCM's impact on thermal

performance while, at the same time, these criteria may also elucidate the need for more concern in order to reach more rational levels of resource consumption. Johansson et al. (2012) demonstrated (in their analysis of the global range of energy uses) that almost 33% of the energy generated is used for building operations and most of this energy is used for air-conditioners to provide thermal comfort for occupants. They showed the possibility of reducing the total global energy use for heating and cooling by 46% in 2050 (compared with 2005) by using best practices in design, construction, and building operation technology—even with increasing demand of thermal comfort inside buildings.

To characterize the influence of PCMs on thermal performance, certain objective data needs to be realized by a data extraction method to support the assessment of utilizing PCMs in building enclosures (Mavrigiannaki and Ampatzi 2016). Data extraction is the act or process of retrieving data out of (usually unstructured) data sources for further data processing (Vithal 2016). The extracted data come from unstructured data sources with different data formats. The unstructured data for this research came in the form of indexes and included total time from connecting sensors to export data. Using this method is useful for having the data in understandable forms for certain times. Also, it is beneficial for sorting and arranging data in order to assess thermal performance of buildings—as it supports classifying data for analysis and clarifying tracking sources for several parameters that can affect data analysis. This method has been used to clean objective data for the assessment, which was used to identify how PCMs can affect the thermal performance of a building. This data includes:

- Profiles of wall temperatures with and without the PCM layer,
- A set of data for different specimens for each configuration,
- A chart view of sensors readings for all wall layers,
- Temperature changes in the PCM (and exterior/interior temperatures),
- Temperatures across walls showing the differences between the normal wall and PCM wall, and
- Temperature profile changes during the melting and freezing process.

3.10.1.1 Evaluation Criteria to Characterize a PCM's Influence on Thermal Comfort

Thermal comfort as defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is the state of mind that expresses satisfaction with the surrounding environment—as assessed by subjective evaluation. Thermal comfort is required by ASHRAE Standard 55-2013 for Human Occupancy (ASHRAE 2013). Therefore, providing a comfortable thermal environment that satisfies its occupants is an essential consideration for building designers and builders.

Maintaining thermal comfort in building construction is one of the most important aims of HVAC systems. Normally, the suggested room temperature is 23.5-25.5 ºC in the summer and 21.0-23.0 ºC in the winter (Zhou et al. 2012). Thermal comfort is a combination of a subjective feeling (person-related) and objective feeling (environment-related) (Fanger 1972). There are a number of factors that influence thermal comfort. According to the International Organization for Standardization ISO (1984), the six primary factors that directly affect thermal comfort can be grouped into two categories: personal factors and environmental factors. Each of these groups has different factors that affect thermal comfort. Environmental factors include air temperature, radiant temperature, relative humidity, and air velocity; personal factors include clothing insulation and activity level.

Most assessments of thermal comfort represent a combination of subjective data (how building occupants feel) and objective data (environmental parameters in a building) (Martinez 2016). Since the experiments have been conducted by using a test apparatus in an enclosed system focusing on building design, this study used objective data only (specifically the temperature in different settings) to assess the impact of PCMs on thermal comfort.

This research focuses on the thermal performance of a building and therefore, the objective data has been considered based on different amounts of a PCM, different insulation thickness, and different climate scenarios—as well as changing the positioning of the PCM layer. The data was collected through multiple laboratory experiments for all specimens to compare the control wall (without PCM) to the experimental PCM wall. Moreover, this research focuses on interior and exterior temperatures as a significant element for the evaluation criteria to characterize the influence of PCMs on thermal comfort. The exterior temperatures were constant across all series

of tests. The temperatures were measured at one-minute intervals for all experiments with the same instrument and sensors in two cycles of climate conditions.

The interior surface temperature used in all experiments to indicate the differences from PCM positioning on thermal comfort used a metric for thermal comfort degree minutes (CDM) for hot and cold periods of the tests (Abuzaid and Reichard 2018). This research developed metrics termed Cooling Comfort Degree Minutes (CCDM) and Heating Comfort Degree Minutes (HCDM) that integrate the difference between room temperature set points and recorded surface temperatures against a temperature threshold (replicating the thermostat reaction range) for each PCM position. The following equations represent the metrics for CCMD and HCMD:

$$\mathrm{CCDM_{th}} = \sum \left| \, t_{s,i} - t_{thc} \, \right| \cdot \Delta m \quad \text{for all } t_{s,i} \geq t_{thc}$$

$$\mathrm{HCDM_{th}} = \sum \left| \, t_{s,i} - t_{thh} \, \right| \cdot \Delta m \quad \text{for all } t_{s,i} \leq t_{thh}$$

where

$t_{s,i}$ … the interior surface temperature in °C

t_{thc} … the reference (threshold cooling) temperature in °C

t_{thh} … the reference (threshold cooling) temperature in °C

Δm … the time interval in minutes

3.10.1.2 Evaluation Criteria to Characterize a PCM's Influence on Energy Savings

Energy savings in building applications is important during different seasons and represents a challenge in many areas. PCMs are considered to be one such advanced energy technology for thermal energy storage systems that could address this issue. There are different criteria to describe the impact of PCMs on energy savings. Dincer (2002) and Mavrigiannaki and Ampatzi (2016) discussed and proposed the most significant criteria that can be used to evaluate a PCM's influence on energy savings. These criteria include six main groups, which are: context and application, element attributes, thermal properties, element performance, implementation aspects, and test conditions. In the first group (context and application), there are different parameters that effect the influence of PCMs on energy savings. These parameters are element, application, climate, season, auxiliary system, control, and internal gains. The parameters of the second group (element attributes) are PCM type, PCM amount, and thickness. For the third group (thermal properties), the parameters include: energy density, thermal capacity, specific heat capacity, conductivity,

temperature range, super cooling, storage duration, and discharge time. The parameters for the fourth group (element performance) are latent heat storage effect, surface temperature, and room temperature fluctuation. For the fifth group (implementation aspects), the parameters include: cost, environmental risk, health/safety, lifetime of the material, and finishing design. The last group of the criteria, which is test conditions, has two parameters: method of investigation and method of verification.

Since this research has been conducted using laboratory experiments in an indoor environment and the assessments used the same PCM material with different implementations, it can be said that the tests used certain criteria from the aforementioned groups to describe the impact of PCM positioning on energy savings. These criteria include element, application, climate (hot/cold), and position from the application and context group, along with PCM quantity and insulation thickness from the elements attribute group. Also, the tests used in this research include surface temperature and room temperature fluctuation from the element performance group. Moreover, all these criteria take into account the method of investigation and method of verification as parameters for test conditions criteria to evaluate the effect of PCMs on energy savings.

To characterize a PCM's influence on energy savings, load shifting time (LST) has been measured in all configuration types of the test during heating and cooling processes. This measurement investigated the impact of a PCM's position on LST. The analysis for this evaluation was based on the comparison of the crossover points of temperatures when changing from cold to warm phases and vice versa in the different experimental cycles. The recorded time has been considered as an indicator for the amount of peak-hour shift that could be achieved for a given assembly. The underlying assumption is that any capability of capturing internal thermal loads of heating or cooling processes and shifting them to off-peak periods could contribute to energy savings, either through short term changes in climatic boundary conditions at the shifted time (e.g., use of economizers), or alternative grid demand and generation cost.

The analysis used an arithmetic and graphical assessment method through scaled result diagrams to evaluate the ability of latent heat storage in different positions to shift peak loads and to discuss notable savings potential. The interior surface temperature used in all experiments indicated the differences of PCM positioning on energy savings by using metric for load shifting time (LST). This metric has been used to measure the time lag of load shifting in hot and cold periods of the tests. The developed metric was used to calculate the difference between load shifting time for the

reference wall (specimen without PCM) and the other walls (specimen with PCM in exterior and interior positions). The reference point of this calculation is the time when the exterior temperature crosses the surface temperature threshold and switches between hot and cold periods.

The following equation represents the metric of LST in cold and hot periods for each position (i.e., the equation for exterior position calculation):

$$\mathrm{LST} = \left(\mathrm{T}_{\mathrm{EPts,i}}\right) - \left(\mathrm{T}_{\mathrm{EPte}}\right) \quad \text{at } \mathrm{EP}_{\mathrm{ts,i}} \text{ and } \mathrm{EP}_{\mathrm{te}} = \mathrm{T}_{\mathrm{Avg\ ts,i}}$$

Where

$\mathrm{T}_{\mathrm{EPts,i}}$ … the time of exterior position (in mins) at interior surface temperature

$\mathrm{T}_{\mathrm{EPte}}$ … the time of exterior position (in mins) at exterior temperature

$\mathrm{T}_{\mathrm{Avg\ ts,i}}$ … the time of (in mins) at average surface temperatures of all positions

The assessment of LST depends on the crossing time of the exterior temperature, the interior surface temperature, and the average surface temperatures of all positions of the specimens. Calculating load shifting time has been used in this research to demonstrate the effects of different positions of PCMs in building enclosures, different amounts of PCMs, and different thicknesses of XPS integrated with PCM on thermal performance by comparative analysis.

4 RESEARCH DESIGN AND OVERVIEW

4.1 RESEARCH STAGES

The intent of this research is to investigate the impact that PCM composite materials may have on energy savings and thermal comfort when implemented in building enclosures. Specifically, this study examines the effects of the position of a PCM within a building enclosure under different climate scenarios. This research assesses the variation of PCM positioning in a building enclosure to investigate the potential opportunities of implementing them as thermal storage in order to reduce the heating and cooling loads and to improve thermal occupant comfort in indoor spaces. Furthermore, this research collects data and measurements from practical experiments to gain a better understanding of material property and impacts.

As shown in Figure (19), this research investigates the positioning of PCMs in building enclosures and studies their impact on energy savings and thermal comfort in three main stages:

1. Theoretical Stage
2. Practical Stage
3. Review and Validation Stage

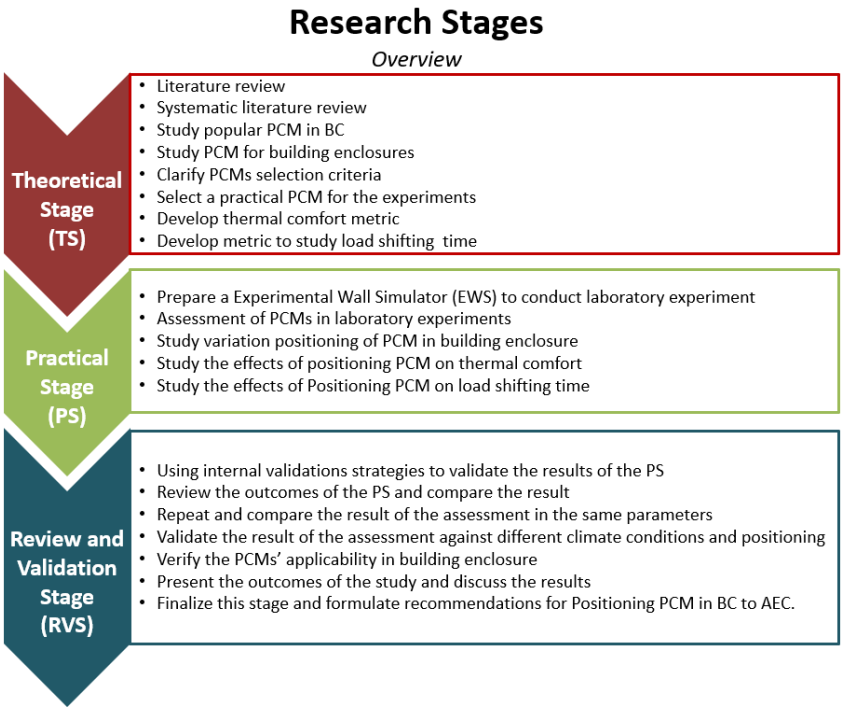


Figure (19) Three main stages of research.

4.1.1 Theoretical Stage

This stage includes a systematic literature review of the existing applications of PCMs in different fields. The systematic literature review has been conducted to study the general characteristics of PCMs, their successful applications in different fields, and criteria of selecting PCMs for building applications. Then, one practical and available PCM, which could improve building performance according to their properties, has been considered as a sample material to be assessed and examined in building enclosures. This stage includes the following steps:

1. Apply the systematic literature review,
2. Study the most popular PCMs and their applicability (especially in building construction),
3. Study existing PCM applications in hot and cold climates,
4. Clarify PCMs selection criteria,
5. Study PCMs that are available and define their applicability for implementing in building enclosures,
6. Select the most functional PCMs to test their applicability of implementation in building enclosures according to their properties, and
7. Identify the selected PCMs and their properties,
8. Study the requirement of laboratory experiments, their instrumentation, and measurement tools setup, and
9. Develop metrics for evaluation.

At the end of this stage, the specification and properties of the selected PCM were clarified and prepared for the practical stage.

4.1.2 Practical Stage

After studying and selecting the applicable PCMs, the practical stage commenced. This stage utilizes laboratory experiments to test the research hypotheses and discuss the positioning of a PCM within building enclosures and its utilization for thermal performance. Figure (20) shows the cycle of laboratory experiments.

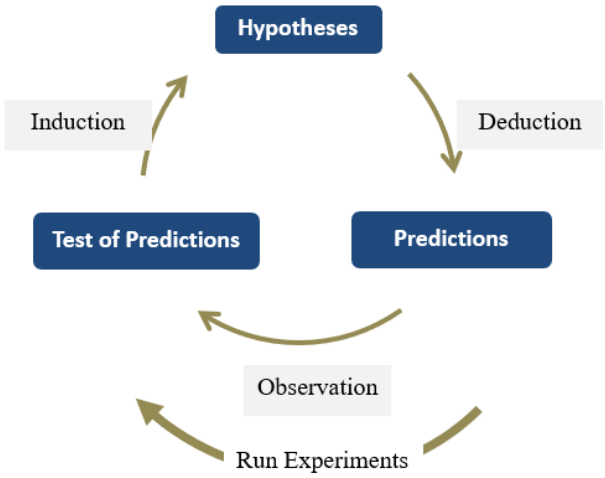


Figure (20) Cycle of laboratory experiments.

In this stage, laboratory experiments were conducted, and an environmental test apparatus was selected to test one PCM in different positions in regard to thermal performance. The test apparatus was placed indoors within the laboratory facilities of the Department of Building Construction, which enabled the testing of PCMs under controlled climate conditions, while conducting different climate scenarios for selected periods of time. Performing the testing in this apparatus allowed the researcher to monitor and control experimental and environmental conditions and parameters as well as to mitigate outside influences that may have affected test results.

The same apparatus was used for all tests with the same properties, dimensions, and equipment. The apparatus was enclosed along four sides and opened on one side (where the enclosure specimen was placed). The experiments were conducted under different climate scenarios and within different temperature ranges. During the laboratory experiments, the ability of PCMs to improve thermal comfort in buildings was tested, and as well as their ability to shift peak loads to off peak times.

The practical stage includes the following steps:

1. Prepare the apparatuses to conduct the practical experiment,
2. Perform a calibration test for sensors to verify their reading accuracy,
3. Create an assessment baseline of the experiment,
4. Evaluate the performance of the PCM in different climate scenarios,

5. Place selected PCMs in the building enclosure and run different climate scenarios, measuring the differences in temperatures, and studying the effects of the climate condition on the performance of the PCM,
6. Apply the PCM in different positions to evaluate and assess the applicability of utilizing PCMs in building enclosures and study the effects on thermal comfort and energy savings,
7. Define the applicability of PCMs to improve thermal comfort,
8. Define the applicability of PCMs to shift part of the heating and cooling load to off-peak hours when there is less energy demand within utility grids, and
9. Verify the PCM's properties as a thermal energy store that can be used in building enclosures.

4.1.3 Review and Validation Stage

To validate the results of the laboratory experiments, internal validations strategies have been used to verify the results of the practical stage. Different climate scenarios with different input factors were used to realize the validation strategy by verifying the opportunity of utilizing of PCMs in building enclosures (and especially in wall systems).

This approach analyzes the outcomes and presents results of the assessment through a validation of the results. This stage includes the following steps:

1. Repeating of the assessment test of the specimens several times to verify the result as internal validation,
2. Comparing the result of selected specimens in laboratory experiments with other specimens (e.g., internal position vs. external position, 1 layer of PCM vs. 2 layers of PCM, and 1 layer of XPS vs. 3 layers of XPS) using the same parameters as internal validation,
3. Verify the PCMs' applicability in building enclosures and its functional role to be used in building construction,
4. Analyze the outcomes and present results of the assessment of utilizing PCMs as a building component in building enclosures,
5. Present the outcomes of the study and discuss the results, and
6. Finalize the validation stage and formulate recommendations for the implementation of PCM in buildings construction to the AEC.

After finalizing the review and validation stage, the research introduces an assessment of results that can be used by building owners, building designers, and building contractors to help them in

selecting the proper positioning of PCMs in building enclosures and determining the best implementation strategy depending on climate conditions.

4.2 Research Method Application

Figure (21) shows an overview of the research objectives, methods, and outcomes of the study. It presents the links between the research sections and the internal and external validations.

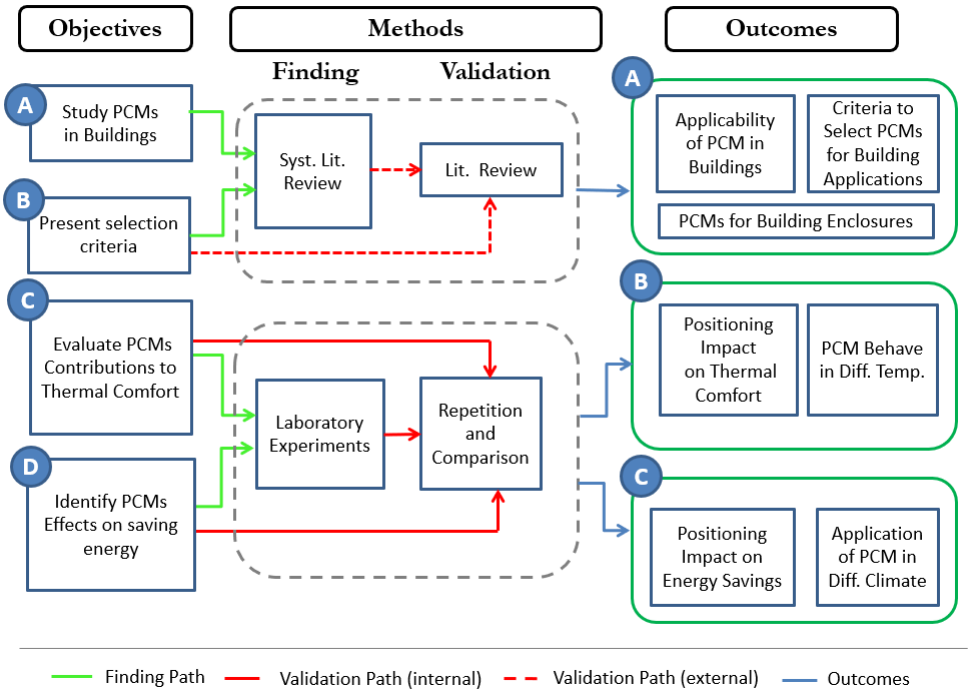


Figure (21) Research design overview.

4.3 Main Steps of the Practical Stage

As mentioned in the research design, the research has been performed in three main stages: a theoretical stage, a practical stage, and a review and validation stage. The practical stage includes laboratory experiments that are described in this section to clarify the process of each test in the research. Laboratory experiments have been used to study the performance of the PCM in different positions within the wall specimen and its impact on the interior space in terms of thermal performance when exposed to different exterior temperatures.

The experiments have been conducted under conditions with identical construction, dimensions, equipment, and building materials—except for the specimens used in the normal wall and the PCM wall. The temperature conditions of the interior and exterior space were measured and compared for all experimental tests. The monitoring of both spaces was performed over three days of hot and cold climate for each position, with data being recorded at one-minute intervals. This practical stage concentrated on a comparison process of different specimens to determine how they behave in different situations and includes six main steps.

In step (1), the experiment facilities were arranged, and the test apparatuses were prepared. The specimens of a 30 x 30 cm (1x1ft) wall—based on a common wood framed stud wall with cavities—were assembled and all cables from the sensors were connected to the data logger and then from the data logger to a computer. In this step, the equipment that was used for comparing, testing, measuring, and simulating cold and hot weather was determined in order to begin experimenting in the next step.

In step (2), a calibration test of the experimental sensors was conducted to ensure they had the same readings and recording temperatures (i.e., identical setup). The result of this test is shown in Figure (22) and the sensors' correlations are included in Appendix 9.3.

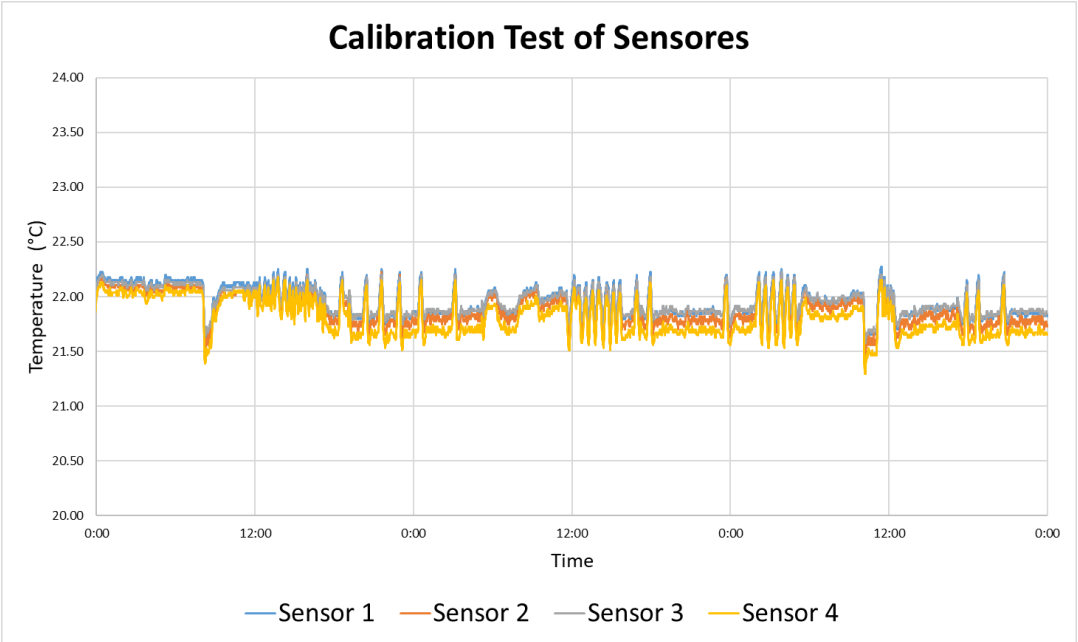


Figure (22) Calibration test of sensors.

In step (3), a specimen for a normal wall (without PCM) was assembled to be used as a baseline for the comparison process of the final output of the experiments. The specimen was tested and exposed to cold and warm periods for three days. The data was collected from this step and used as a reference point within each test configuration to compare between the normal wall and PCM wall to illustrate the effect of PCM positioning on thermal comfort and load shifting time in cold and warm climates.

In step (4), a specimen with PCM in the exterior cavity was assembled and tested. The PCM was placed close to the exterior space between an insulation layer and an oriented strand board (OSB) layer. In this step, cold and hot climate scenarios were applied, and data was collected to illustrate the effect of the positioning of a PCM on thermal performance.

In step (5), the process was repeated for steps (3 and 4), but with placing the PCM in the interior cavity between an insulation layer and gypsum board.

In step (6), all data was collected and processed to be used for interpretation and evaluation. After that, the findings were studied to give a summary of the overall assessment of placing a PCM in different positions within building enclosures under different climate conditions. At the end of this step, the outcomes were finalized for review and validation. Figure (23) shows a detailed workflow of the laboratory experiments and highlights the main steps including duration and sequence.

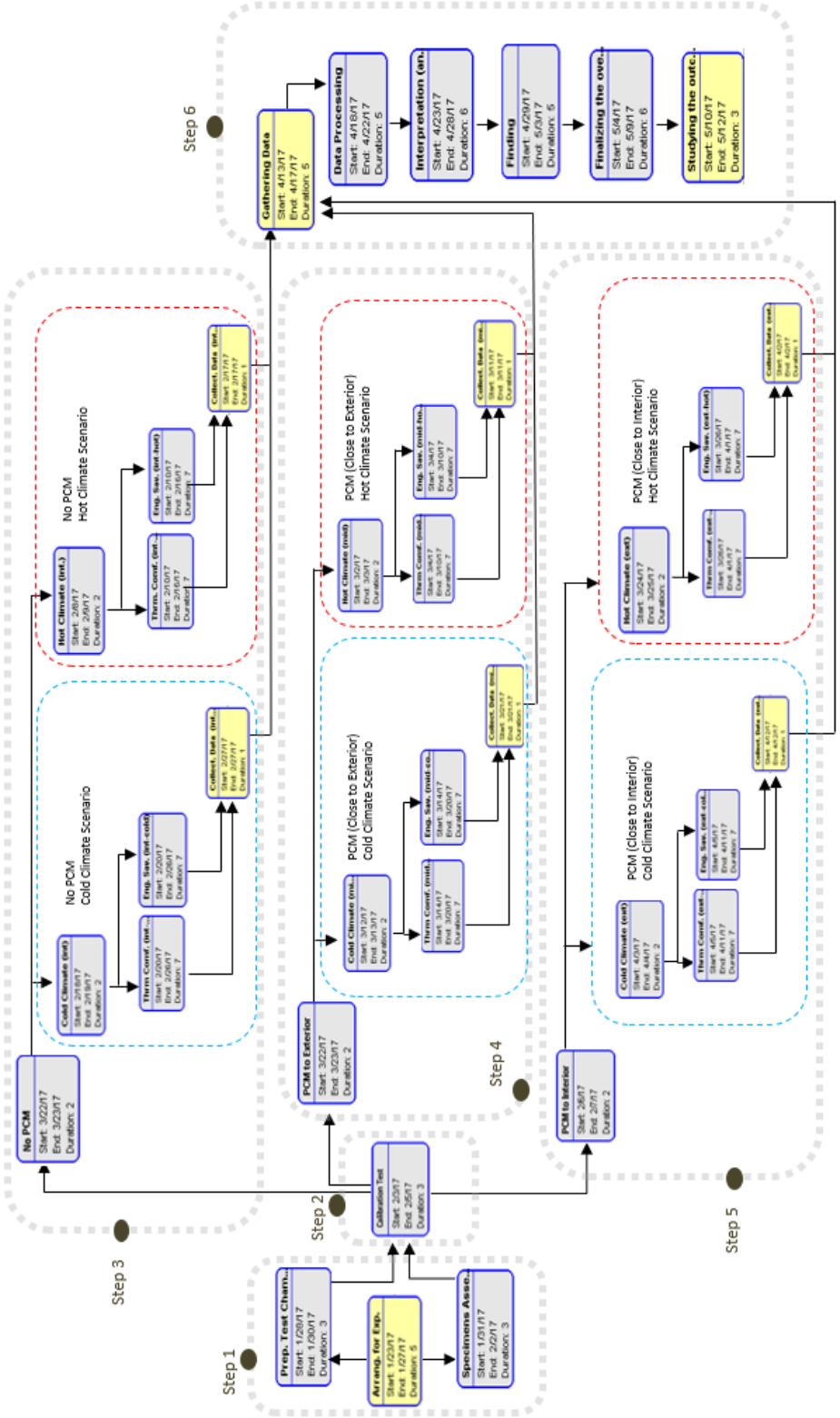


Figure (23) A workflow of the laboratory experiments for each configuration.

5 LABORATORY EXPERIMENTS

A comparative study has been conducted to evaluate the impact of PCM implementation in a laboratory indoor environment to enable the testing of PCMs under controlled climate conditions, while focusing on different dependent variables for fixed periods of time. The test apparatus was placed indoors within the laboratory facilities of the Department of Building Construction in the Building Enclosure and Systems Technology Lab (BEST Lab) in Bishop-Favrao Hall at Virginia Tech. Conducting all tests in a lab setting allowed for the monitoring and control of the experiment's environmental conditions and parameters as well as removing other outside climate influences—such as solar radiation and winds, which would otherwise affect test results.

5.1 EXPERIMENTAL SETUP

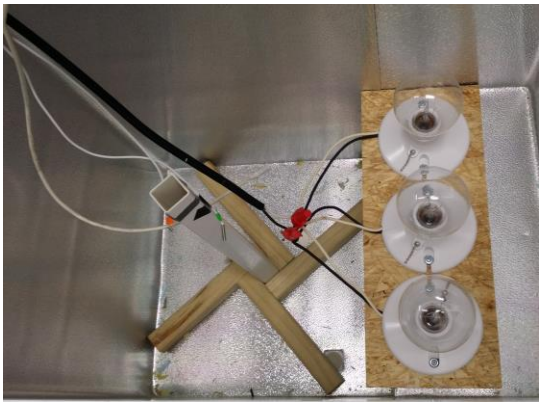
The experiments were conducted in the same laboratory space, utilizing the same material properties, dimensions, equipment, and temperature ranges to study the differences between the results collected from the different positions (exterior and interior sides of a wall cavity) of a PCM in a building enclosure in comparison to a wall without PCMs. These experiments were conducted under controlled conditions for a set running time for heating and cooling process of 12 hours each. The evaluation included monitoring how PCMs overall behave in different temperature ranges and positions, as well as their ability to reduce temperature fluctuations across wall components and influence peak-load shifting.

The Experimental Wall Simulator (EWS) was used to conduct the laboratory experiments. EWS has two main components:1) a test apparatus based on a 5.0 cu ft chest-freezer and 2) specimens to simulate different types of wall configurations. The chest-freezer was utilized to facilitate and control the exterior temperatures. While the freezer provided the cooling source for cold exterior climate conditions, three 40 W incandescent light bulbs provided the heating source to create the hot exterior temperatures within the chest compartment.

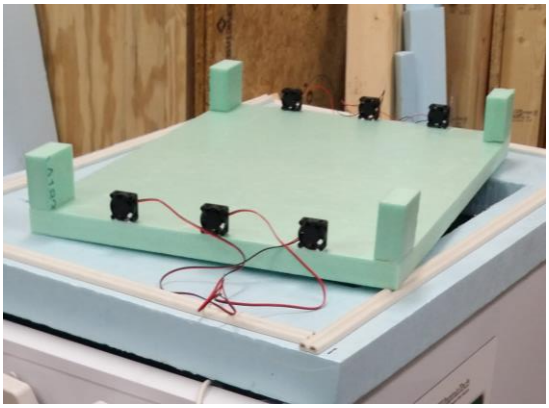
The experiments were conducted by creating cold and warm periods to monitor the PCM's behavior in specimens and study their impact on the interior surface temperature. The PCM was further tested in an exterior and interior position of the building enclosures to assess any changes and compare them with the baseline wall specimen that did not contain a PCM layer. Figure (24) shows the experimental setup of the study and illustrates how the equipment and devices were connected.

Figure (24) Experimental setup with data logger and computer.

Since the volume of the exterior climate side in the apparatuses is limited, the radiative contributions of the heating source had a significant impact on the exterior surface temperatures of the specimen. Thus, the radiant shield was placed at a distance of 5 cm from the exterior surface and equipped with six miniature fans for controlled constant convection along the specimen surface. Figure (25) shows the heating source and radiant shield that have been used in the experiments.



a)



b)

Figure (25) a) Heating source and b) radiant shield with six fans.

In this study, the thickness of the gypsum board and the OSB enclosing of the wall cavity were kept identical across all test series. The interior temperature was controlled through the fixed air temperature of the closed 21 m^2 lab space. In all experiments, eight thermocouple sensors were used (HOBO type TMC-HD and TMC-HC) to record temperatures. Two sensors were used to measure temperatures with relative humidity (type RHPCB) to capture exterior and interior conditions. To capture the changes in the PCM phase, a temperature sensor was placed on each side of the PCM. Figure (26) shows the placing of a PCM layer in the exterior and interior positions with attached sensors on the sides—as well as the interior surface of the specimen (gypsum board) with an attached sensor to record interior surface temperature.

a) b) c)

Figure (26) a) PCM in exterior position; b) PCM in interior position; and c) interior surface of specimen.

The interior surface temperature is important for comparing different positions of PCM application. In this case, a shield of XPS was used to protect the sensor of the interior surface from being directly affected by the interior air-conditioning system or any other effect that could occur in the lab (such as people movement, which could also affect sensor readings). The shield was designed as an enclosed box with one side open to keep the sensor in a ventilated space and prevent generating any hot or cold temperatures. Figure (27) illustrates schematically the EWS with interior and exterior setup configurations as well as the position of sensors utilized in the study.

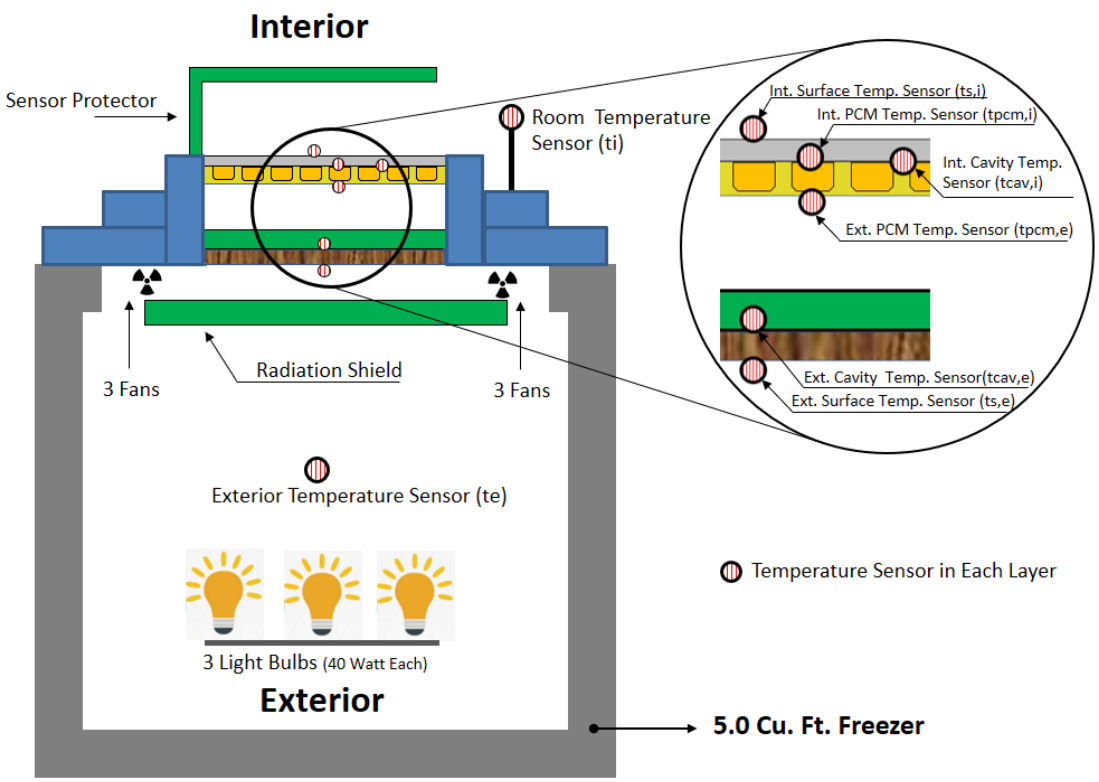


Figure (27) Schematic diagram of the experimental setup and sensor positions.

The experiments were conducted under identical conditions for all wall specimens. They also used the same equipment for measuring and collecting data. Wireless HOBO ZW data nodes and sensors were used to measure and log the temperatures of the interior (room-side) and exterior (chest-side) air, inside and outside surface, and several other temperatures across the different layers of the wall components. Table (4) shows the taxonomy used for referencing these sensors and their correlating positions throughout this study.

Table (4) Sensors and positions.

Sensor Name	Position
t_i	Interior room temperature
$t_{s,i}$	Interior surface temperature
$t_{cav,i}$	Interior cavity temperature
$t_{pcm,i}$	Temperature at interior side of PCM
$t_{pcm,e}$	Temperature at exterior side of PCM
$t_{cav,e}$	Exterior cavity temperature
$t_{s,e}$	Exterior surface temperature
t_e	Exterior temperature

The data loggers were configured to collect data at one-minute intervals. For controlling the time of warm and cold periods, wirelessly programmable WEMO switch devices were used to control the duration of hot and cold exterior climate cycles. To maintain temperatures during these periods at fixed "exterior" levels within the chest chamber, this study used two digital temperature controllers (WILLHI WH 1436) to control the exterior set point temperatures during the hot and cold climate periods for each scenario. Figure (28) shows the control panel utilized in the study and devices that have been used in the experiments for controlling temperatures and recording data.

a)

b)

c)

d)

Figure (28) a) Control panel assembly; b) data logger node and receiver; c) timer modules; and d) temperature controller.

5.2 DESCRIPTION OF SPECIMENS

The design of the studied specimens was based on a common wood framed stud wall with cavities, which were then filled with different PCMs and insulation configurations (expect for the reference wall, which had no PCMs). The specimens were mounted into frames made of extruded polystyrene (XPS) foam and consisted of gypsum board for the internal sheathing layer, XPS for the insulation layer(s), the PCM (bio-based PCM mat), and an oriented strand board (OSB) for the external sheathing layer.

The insulation type was a 2.5 cm thick layer of XPS for a better linear comparison. All specimens had the same dimensions of 40 x 40 cm with total thickness of 12.2 cm. Lightweight building materials such as gypsum plasterboards, XPS, and OSB were used with relatively low thermal mass in each test.

Four base configurations for the tests were investigated in the laboratory experiments, varying either the number of PCM layers (**P**) or the layers of insulation (**X**) as follows:

Configuration 1: For 1 layer of PCM and 1 layer of XPS (indicated by **P1X1**)

Configuration 2: For 1 layer of PCM and 3 layers of XPS (indicated by **P1X3**)

Configuration 3: For 2 layers of PCM and 1 layer of XPS (indicated by **P2X1**)

Configuration 4: For 2 layers of PCM and 3 layers of XPS (indicated by **P2X3**)

Furthermore, within each of these configurations, there were three additional specimens to represent the positioning during the test in the laboratory experiments. These specimens are:

Specimen 1: Without any PCM (indicated by **NP**)

Specimen 2: With PCM layer(s) on the exterior side of the cavity (indicated by **EP**)

Specimen 3: With PCM layer(s) on the interior side of the cavity (indicated by **IP**)

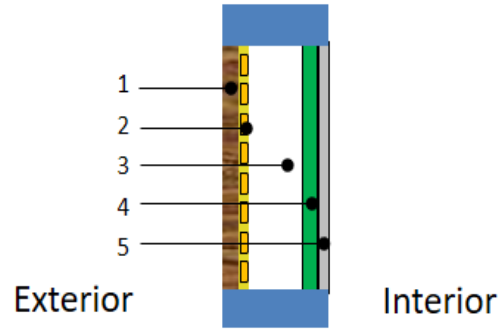
In total, 12 specimens were used in the laboratory experiments and described according to their components with the aforementioned abbreviation letters to indicate their positions and layers. For example:

EP1X1: For the specimen with exterior positioning of 1 layer of PCM and 1 layer of XPS and

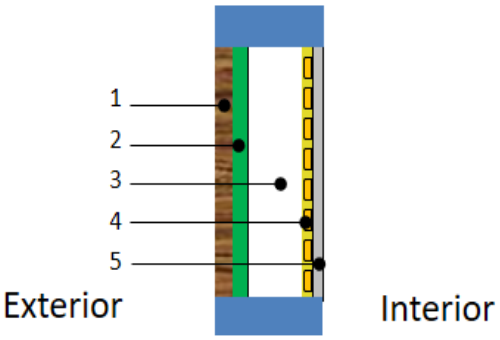
IP2X3: For the specimen with interior positioning of 2 layers of PCM and 3 layers of XPS.

Figure (29), Figure (30), Figure (31), and Figure (32) demonstrate the tested specimens with detailed components and thicknesses in different test configurations.

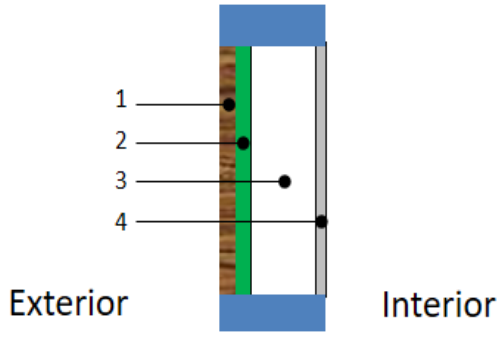
P1X1: 1 Layer of PCM & 1 Layer of XPS



EP1X1		
Exterior Position (EP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of PCM	0.5 cm
3	Air Gap	6 cm
4	1-Layer of XPS	2.5 cm
5	Gypsum Board	1.3 cm



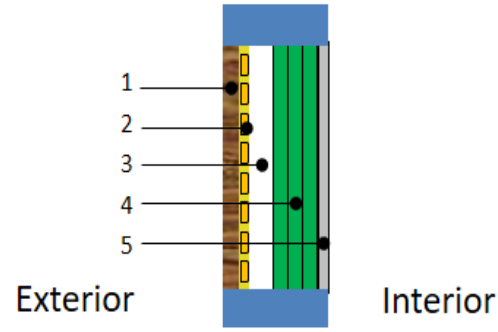
IP1X1		
Interior Position (IP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6 cm
4	1-Layer of PCM	0.5 cm
5	Gypsum Board	1.3 cm



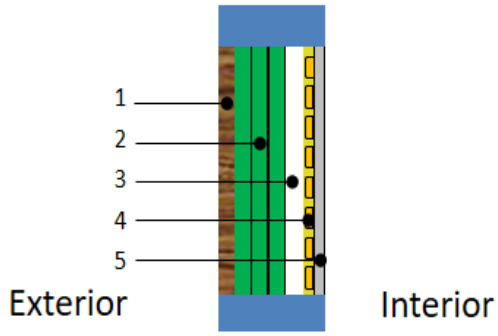
NP1X1		
No PCM (NP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6.5 cm
4	Gypsum Board	1.3 cm

Figure (29) P1X1: Specimens (sections, layers, and thickness).

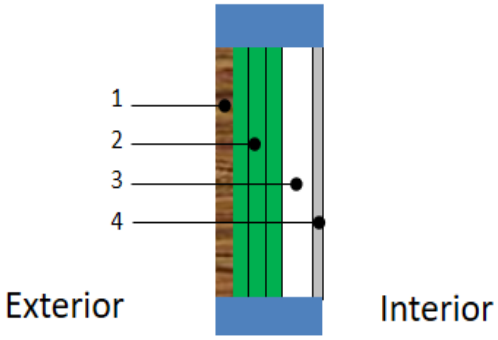
P1X3: 1 Layer of PCM & 3 Layers of XPS



EP1X3		
Exterior Position (EP)		
Layer ID	**Description**	**Thickness**
1	OSB Sheathing	1.9 cm
2	1-Layer of PCM	0.5 cm
3	Air Gap	1 cm
4	3-Layers of XPS	7.5 cm
5	Gypsum Board	1.3 cm



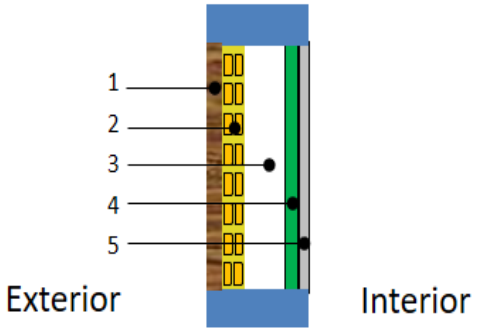
IP1X3		
Interior Position (IP)		
Layer ID	**Description**	**Thickness**
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1 cm
4	1-Layer of PCM	0.5 cm
5	Gypsum Board	1.3 cm



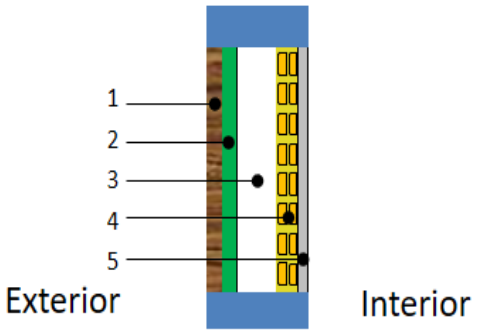
NP1X3		
No PCM (NP)		
Layer ID	**Description**	**Thickness**
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1.5 cm
4	Gypsum Board	1.3 cm

Figure (30) P1X3: Specimens (sections, layers, and thickness).

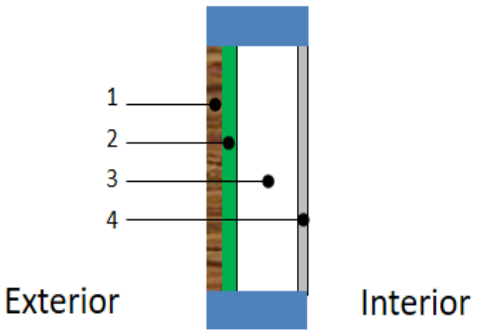
P2X1: 2 Layers of PCM & 1 Layer of XPS



EP2X1		
Exterior Position (EP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	2-Layers of PCM	1 cm
3	Air Gap	5.5 cm
4	1-Layer of XPS	2.5 cm
5	Gypsum Board	1.3 cm



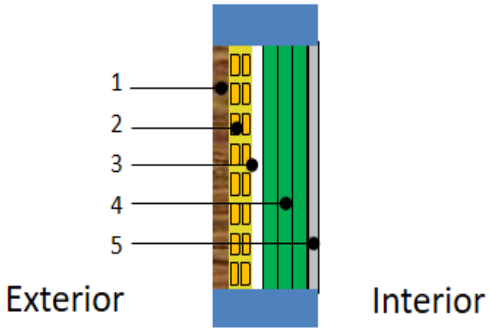
IP2X1		
Interior Position (IP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	5.5 cm
4	2-Layers of PCM	1 cm
5	Gypsum Board	1.3 cm



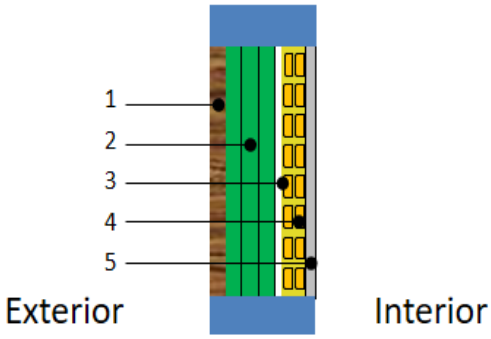
NP2X1		
No PCM (NP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6.5 cm
4	Gypsum Board	1.3cm

Figure (31) P2X1: Specimens (sections, layers, and thickness).

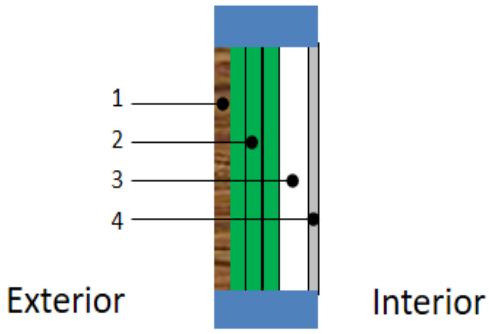
P2X3: 2 Layers of PCM & 3 Layers of XPS



EP2X3		
Exterior Position (EP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	2-Layers of PCM	1 cm
3	Air Gap	0.5 cm
4	3-Layers of XPS	7.5 cm
5	Gypsum Board	1.3 cm



IP2X3		
Interior Position (IP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	0.5 cm
4	2-Layers of PCM	1 cm
5	Gypsum Board	1.3 cm



NP2X3		
No PCM (NP)		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1.5 cm
4	Gypsum Board	1.3 cm

Figure (32) P2X3: Specimens (sections, layers, and thickness).

In all experiments, the same type of PCM (Bio-based PCM mat) was used with a 1-layer or 2-layers configurations. Table (5) lists main properties of the utilized PCM in this study (Phase Change Energy Solutions 2015) and Figure (33) shows the two different sides of the PCM. Also, more details about the PCM have been included in Appendix 9.8.

Table (5) The PCM's properties.

Item	Description / Value
Manufacturer	Phase Change Energy Solutions – (USA- Asheboro, NC)
Material Name	ENRG Blanket Q23 (Bio-based PCM mat) Solid/Liquid phases
Filling	Natural vegetable oils and proprietary blend of emulsifiers, gelling agents, fatty acids, and their derivatives
Encapsulation (thickness)	50 mm (multilayer white polyfilm and foil)
Melting Point	23°C
Latent Heat Storage Capacity	175-250 J/g
Fire Rating	Class A
Thermal conductivity	0.20 W/mK
Weight	2.49 kg/m²

Figure (33) The two different sides of the utilized PCM.

5.3 Pilot Studies and Initial Results

In the early stage of the research, several initial experiments and pilot studies were conducted to ensure that all sensors were properly placed, and the setup of the experiments was well designed to achieve the required objectives. The first set of experiments were conducted under controlled conditions for a set running time for a heating and cooling process of three hours each. The experiments were set for positioning PCM in the exterior cavity of the specimen to see how the PCM reacted during cold and hot periods. The results of these experiments showed the changing of the PCM's temperature, but they did not take advantage of the charging and discharging features of the material. The change in latent heat was very minimal and the PCM did not reach its steady state condition in either periods as shown in Figure (34).

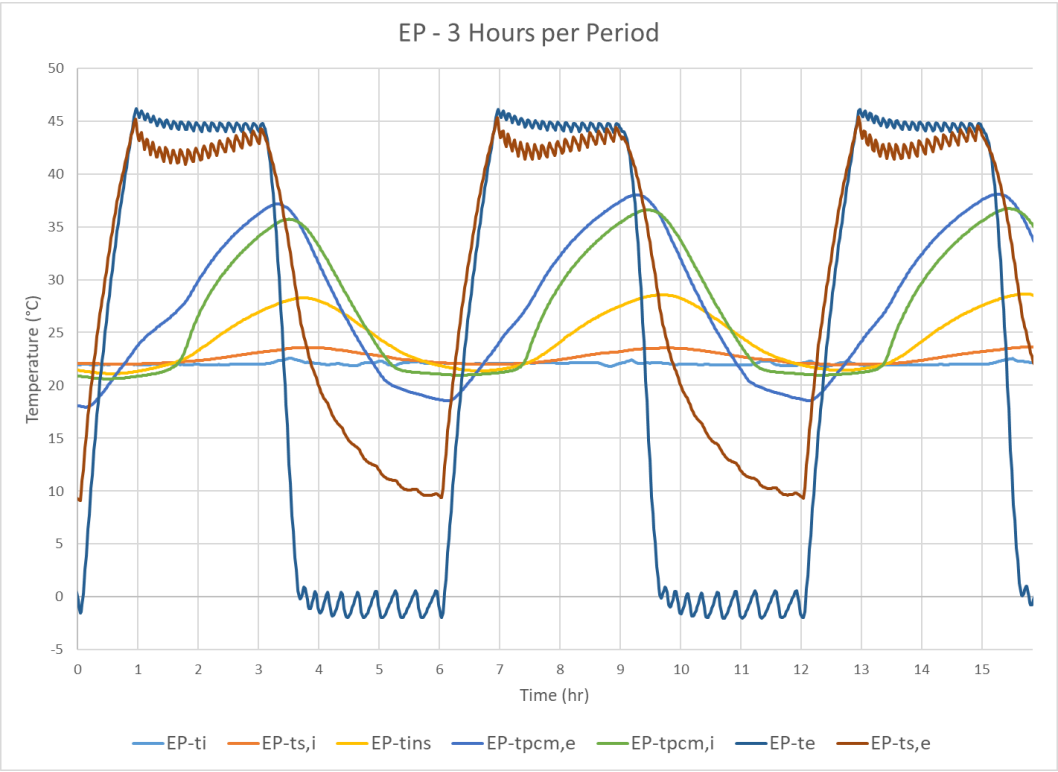


Figure (34) Initial result of three-hour period test.

During the next stage, the setup of the experiment was prepared for the same specimen with the same controlled conditions, but the set running time for heating and cooling process was based on a six-hour test for each period (cold and warm). This set of experiments showed an improvement

in the results regarding the charging and discharging process, although the PCM still did not reach the steady state condition in either periods as shown in Figure (35).

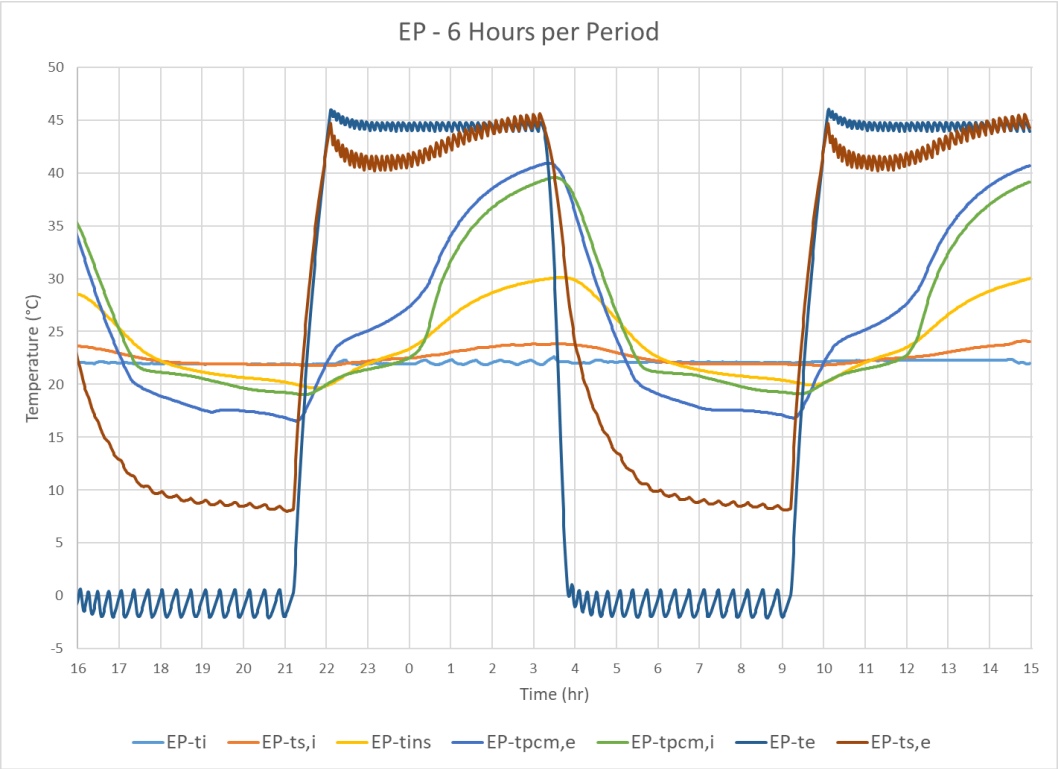


Figure (35) Initial result of six-hour period test.

When the time of each period was increased by three hours, the results of the experiment improved. Overall, the change of PCM temperatures (latent heat) became more noticeable in the hot period, but the change was less in cold period. Therefore, additional tests were conducted by adding six hours for each period to reach 24 hours for the test cycles—including 12 hours for the cold period and 12 hours for the warm period. The experiments with 24 hours of testing time were carried out under the same controlled conditions with each specimen. The results of these experiments show the change of PCM temperatures (latent heat) in both periods. Moreover, the steady state temperature of the PCM was briefly reached in both periods, with better conditions in warm period as shown in Figure (36).

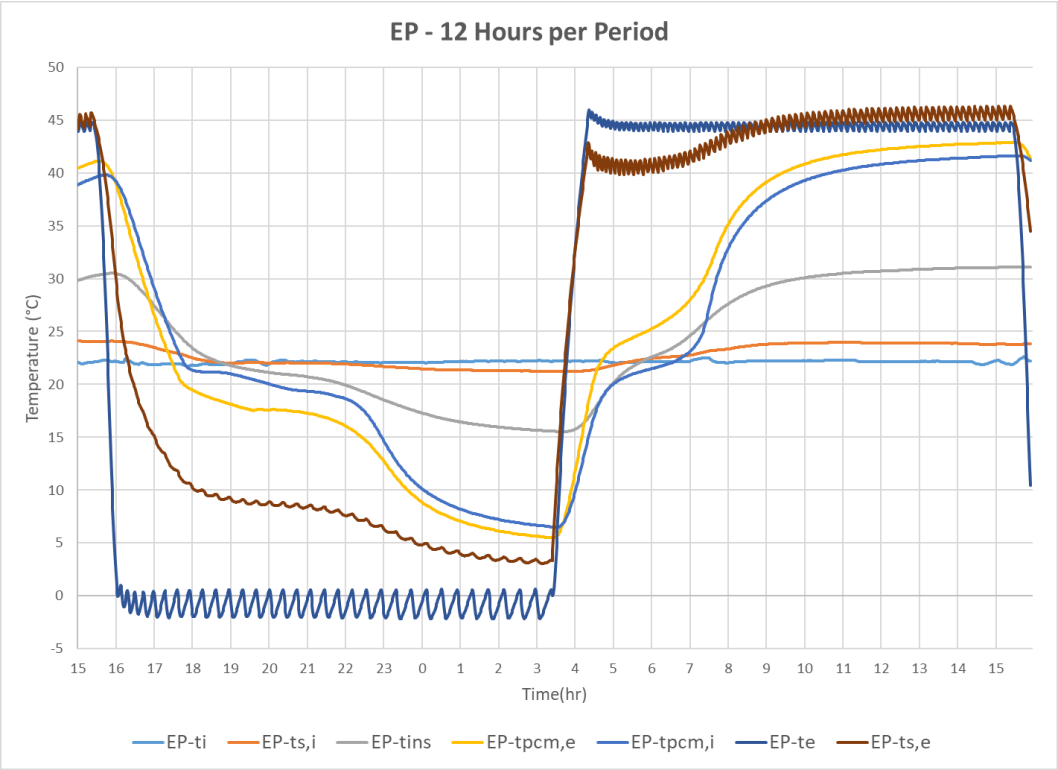


Figure (36) Initial result of 12-hour period test.

After increasing the testing time of the experiments to reach 24 hours in total, a significant change occurred for the exterior surface temperature. When the experiments were conducted during the heating process, an increased heat transfer at the exterior surfaces was detected, where surface temperatures exceeded the recorded exterior air temperatures that were controlled by the thermal sensors of the switching device. The increased heat transfer effect occurred because of the increased radiant heat exchange through the utilization of light bulbs as a heating source, which in turn had an impact on the temperature of the external surface ($t_{s,e}$) of the specimen. This effect was observed across all experiments. More specifically, the effect accrued over time, as more and more heat was absorbed through radiation, bypassing the conduction and convection exchange through the air. Figure (37) shows the effect of the radiant heat exchange on the external surface temperature of the specimen during heating cycles. Therefore, a radiant shield with six miniature fans was added under the external surface in the modified experimental setup to overcome the effect of the radiance—as previously mentioned in the experimental setup section.

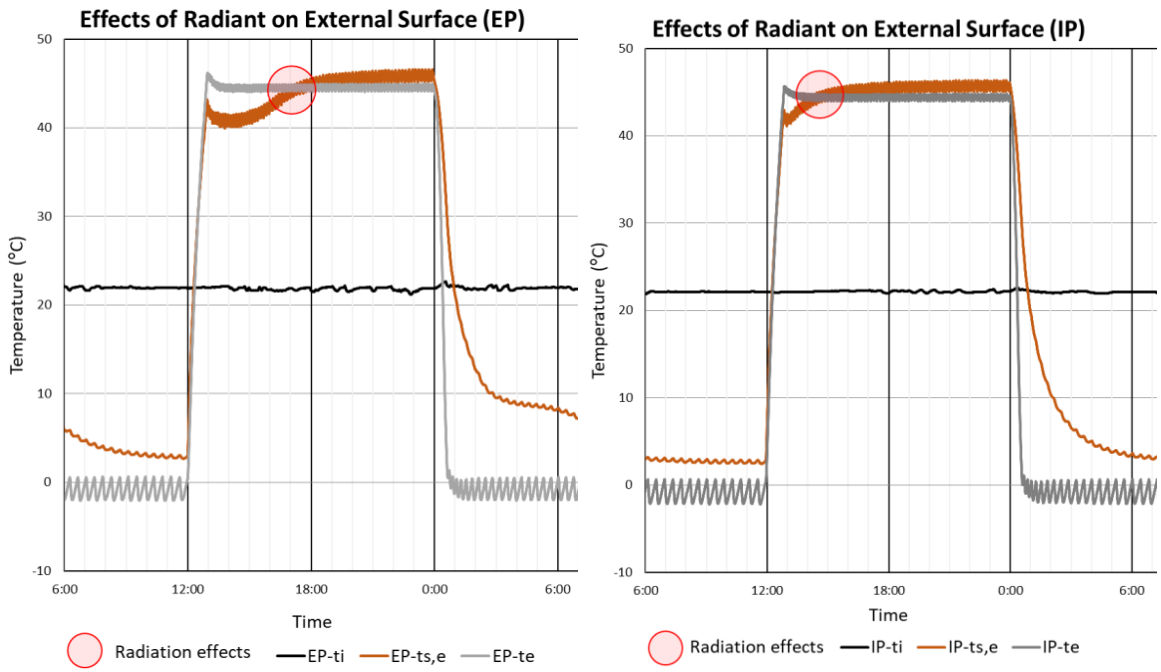


Figure (37) Effect of the radiant heat exchange observed at external surface in the experiments.

5.4 METHODOLOGY OF EXPERIMENTS

The experimental strategies used the desired operating set-points for the boundary of the tests and operative temperature to charge and discharge the PCM during warm and cold periods. The overall data was directly recorded for analysis. The relations between the heating/cooling process and PCM behaviors in different positions have been analyzed.

5.4.1 EXPERIMENTAL PROCEDURE

The objective of this study was to experimentally evaluate the impact of different quantities and positions of a PCM within the building enclosure on thermal performance. The study employed the same experiment with three different specimens for each type of test configuration to assess the impact of different PCM treatments. The three main specimens in each configuration have been explained in a previous section.

Each experiment was conducted for 72 hours with three cycles of 12 hours of cooling and 12 hours of heating each. Each experiment started with a cold period by turning on the freezer for 12 hours

to make sure that the PCM completely reached the solidifying phase. Then, the warm phase was initiated by turning on three light bulbs within the chest freezer to reach and maintain the hot climate setpoint for 12 hours. The 12-hour cycle was selected to achieve complete melting and freezing phases of the PCM through each cycle.

The experiments included monitoring how PCMs behave under different climate conditions and study their ability to reduce air temperature fluctuations for interior spaces. The comparison between a normal wall and a PCM wall was carried out in an enclosed system within one-dimensional measurements. Before starting the experiments, calibration tests were conducted to assure the sensors had identical temperature readings. Also, the boundary (t_e and t_i) for each position test (i.e., EP, IP, and NP) were recorded and monitored to verify that the recorded temperatures during the warm and cold periods were identical.

The controlled setpoint temperatures for the exterior climate were based on the maintained interior laboratory room temperature. Exterior temperatures were held at 45 °C for the hot periods and at 0 °C for the cold periods, while the set point of the room temperature was kept between 21-23 °C, which represents the range of the melting point of the utilized PCM. The recorded indoor temperatures across all experiments showed less than 2 °C of fluctuation. Figure (38) shows an overlay of all recorded interior and exterior temperatures across all the different 72-hour experiment cycles. Relative humidity was monitored and recorded, but not considered for the analysis of this study.

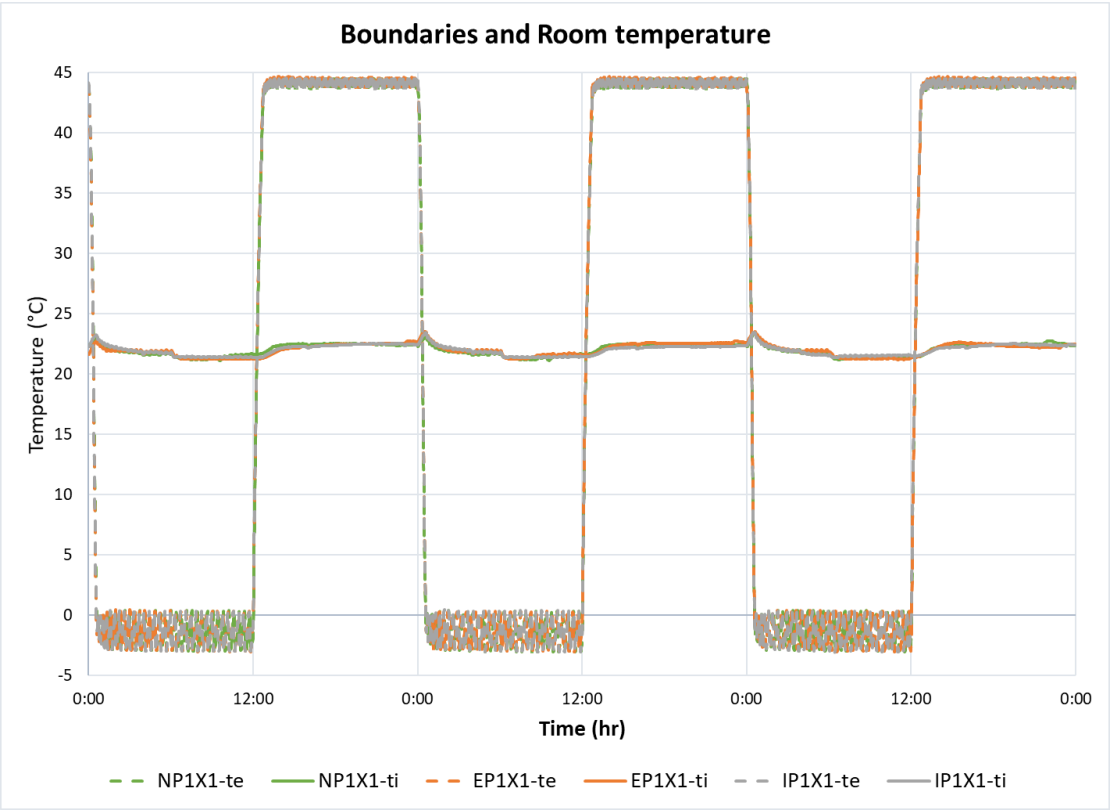


Figure (38) Recorded interior and exterior temperatures during cycles.

5.4.2 Quality Control of Variables

As mentioned in the variables section, the laboratory experiments have two groups of variables. A quality control process was used for the independent variables. This group includes five variables: PCM position, PCM quantity, thickness of insulation, heating and cooling time, and exterior and interior temperatures. These variables can be easily controlled according to their physical properties—except for the heating/cooling time and exterior temperatures (t_e) and interior temperatures (t_i). For heating and cooling time, two digital timers were used to ensure that each test was built on the same duration for cooling and heating during the experiments. For the (t_e) and (t_i) variables, there were three main steps to ensure that the recorded data was within the boundary conditions of the test. These steps have been applied for the interior and exterior boundary conditions as follows:

First Step:

The (t_e) and (t_i) were recorded for 24 hours to identify the range of the boundary conditions of the test. This process was carried out for all specimen tests (NP, EP, and IP) and produced a line chart that illustrated the range of the boundary conditions with an upper control level (UCL) and a lower control level (LCL) for the exterior and interior temperatures. The outcome of this step was presented in an overlapped diagram to ensure the temperatures were compared during the same period. Figure (39) shows a line chart to illustrate the boundary of (t_e) during the tests, and Figure (40) shows the control of the (t_i) boundary during the tests.

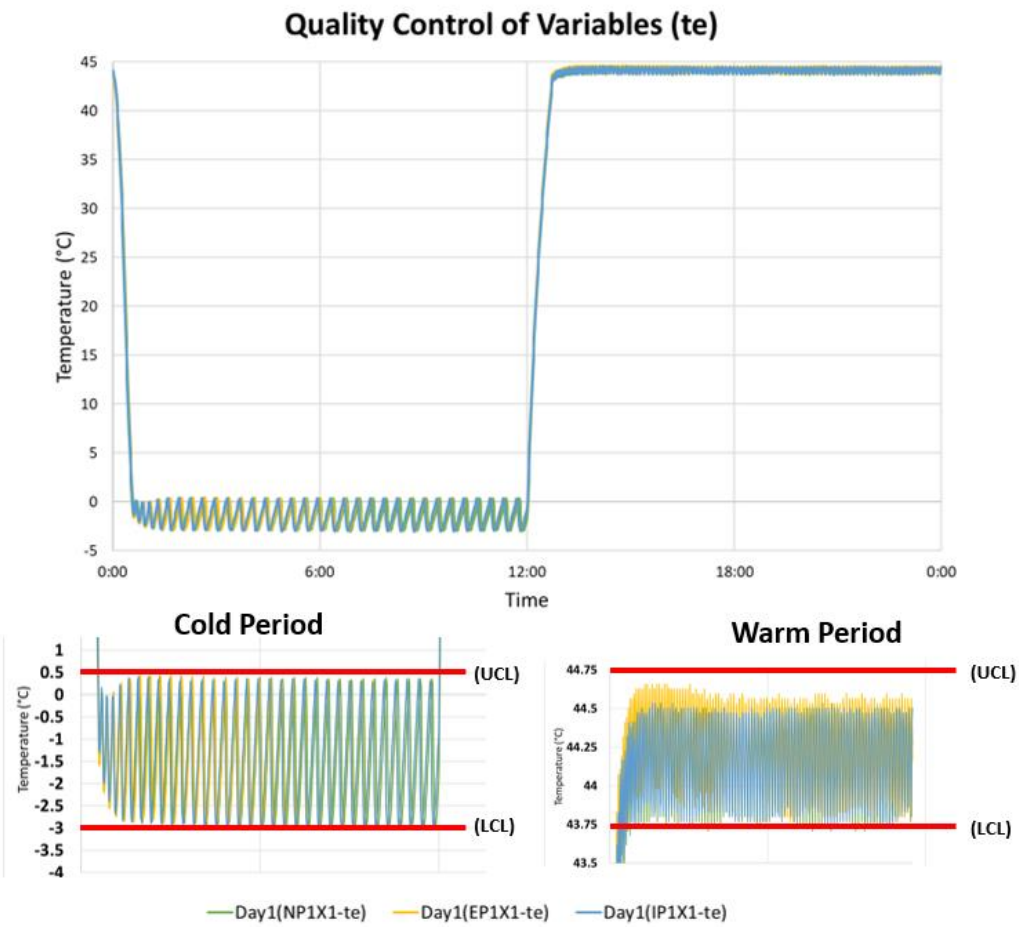


Figure (39) Control of exterior temperature.

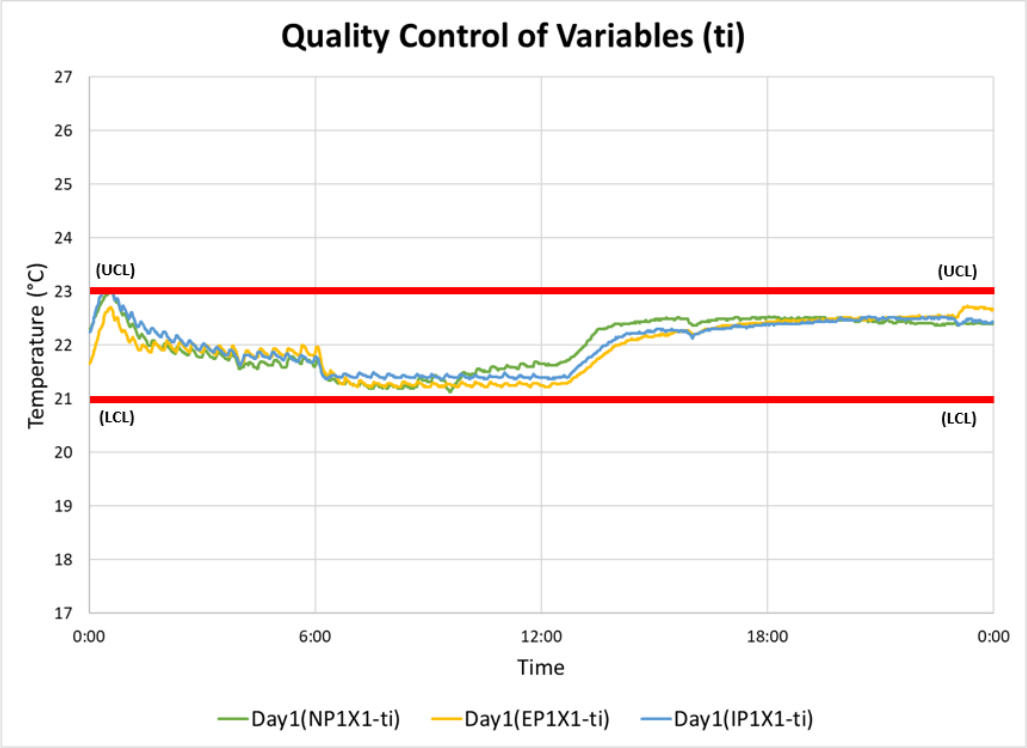


Figure (40) Control of interior temperature.

Second Step:

After identifying the range of the boundaries, the experiment was conducted over the course of three days to verify the upper and lower level of the exterior and interior temperatures. The average temperatures for the three days was calculated and presented for each specimen test (NP, EP, and IP). The outcomes of this step show the comparisons between temperatures during the experiments for the exterior and interior boundaries. Figure (41) shows the average line of the exterior temperatures during the test of each specimen. For the interior temperature, the same process was followed, and the outcomes are shown in Figure (42).

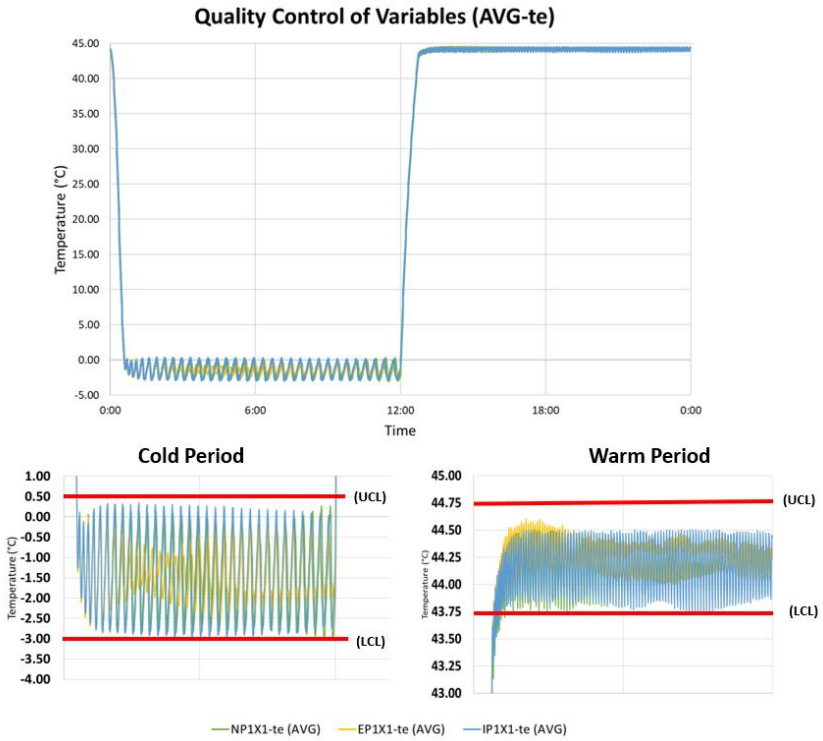


Figure (41) Control of exterior temperature – AVG of 3 days.

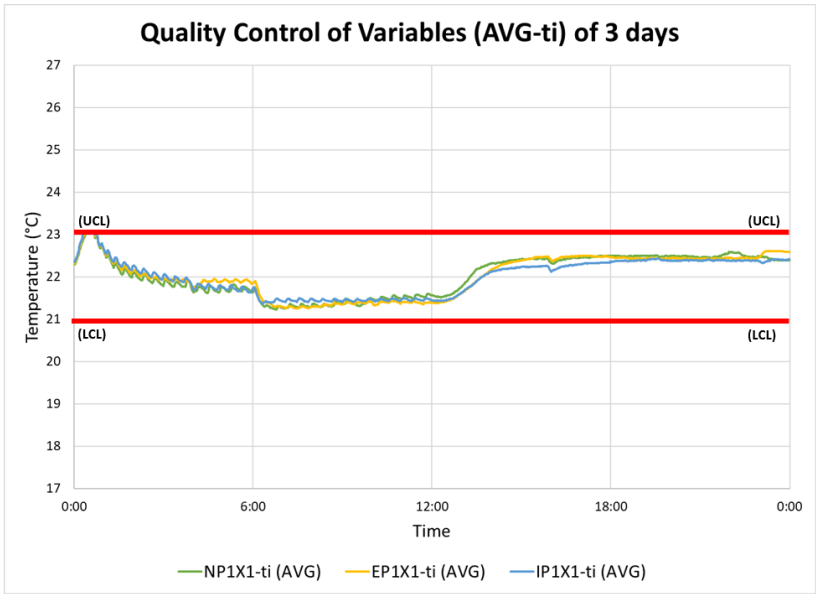


Figure (42) Control of interior temperature – AVG of 3 days.

Third Step:

The average line of the recorded data for each test was simplified by using a walking average line for the required data. A smoothing line was used to reduce the fuzzy lines of the time frame. The following equation was used for this step:

$$t_{n,a}^{m} = \frac{1}{2m+1} \sum_{n-m}^{n+m} t_{n,r}$$

Where:

t	…… temperature
$t_{n,r}$	…… recorded (t) at n
$t_{n,a}$	…… average at (t) time n
m	…… range of t-point (means smoothing)
n	…… time slot of measured point
r	…… recorded t
a	…… average

By using this equation, the smoothing of the average line of each temperature (t_e and t_i) has been presented to verify the boundary of the specimen tests. Figure (43) shows the smoothing line of the exterior temperature after one hour of testing and Figure (44) shows the smoothing line of the interior temperature after one hour of testing. At the end of this step, the range of each boundary was determined to control the outcomes of the exterior and interior temperature readings as independent variables for all experiments. These steps have been followed for all experiments to ensure the temperatures were compared in the same range during the same period.

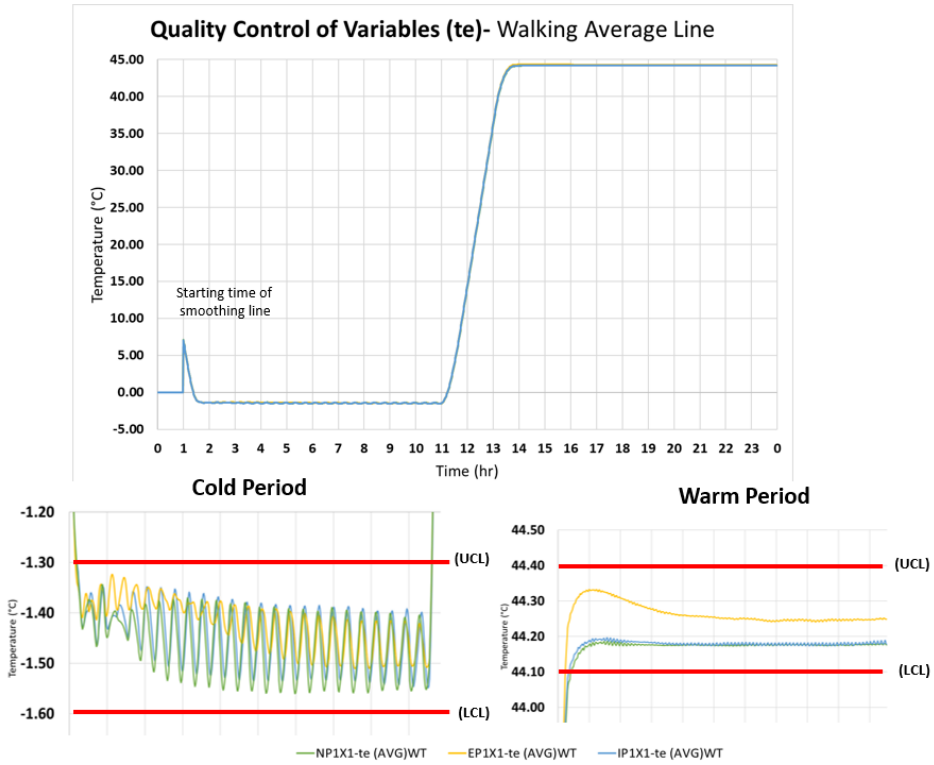


Figure (43) Control of exterior temperature – walking AVG line.

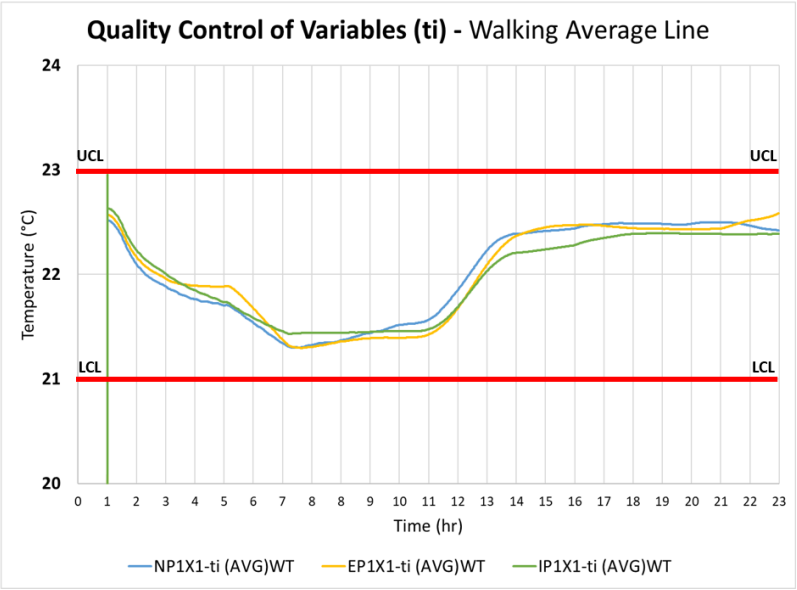


Figure (44) Control of interior temperature– walking AVG line.

5.5 Analysis Methods

The analysis of the experimental results focused on the impact of PCMs in different quantities and positions in terms of thermal comfort and load shifting time during heating and cooling processes. Four main configurations of the tested specimens were analyzed regarding PCM quantity. These configurations are P1X1, P1X3, P2X1, and P2X3 along with NP, EP, and IP to test positioning. For each configuration, the analyses were performed in three stages:

1) Differential result patterns of PCMs in different positions,

2) Analysis of impact of PCM positioning on thermal comfort, and

3) Analysis of impact of PCM positioning on load shifting time.

5.5.1 Differential Result Patterns of PCMs in Different Positions

In the first analysis stage, a quantitative comparison of temperatures over time was carried out to identify areas of difference for further investigation and discussion. The experimental results were cleaned and then presented in graphical form. A comparative discussion of temperature data during the hot and cold phases for each PCM position was conducted with different numbers of PCM layers and different thicknesses of insulation.

After capturing objective data, a review of a three-day period was conducted. However, the first cold and hot temperature periods were less practical for evaluation—as they are considered as a "swing-in" phase and a starting vector of boundary conditions. For detailed analytical evaluations, only the cold and hot temperature periods on the 2nd and 3rd day were reviewed (hours 24-72) and the more identical one was evaluated accordingly. At the end of this stage, an analysis of the impact of PCM positioning (EP, IP, and NP) in terms of thermal comfort and shifting load shifting time was undertaken.

5.5.2 Analysis of Impact of PCM Positioning on Thermal Comfort

The second analysis stage focused on evaluating the impact of PCM positioning on thermal comfort by observing and analyzing differences in surface temperatures. As surface temperatures are critical indicators for thermal human comfort, this analysis developed a metric termed Comfort Degree Minutes (CDM) that integrates the difference between room temperature set points and recorded surface temperatures against a temperature threshold (replicating the thermostat reaction range) for each PCM position. This metric (included below for reference) was previously

explained in detail in the section on evaluation criteria to characterize a PCM's influence on thermal comfort. This evaluation uses two equations, 1) for cold comfort degree minutes (CCDM) and 2) for hot comfort degree minutes (HCDM), as follow:

$$\mathrm{CCDM_{th}} = \sum \left| \mathrm{t_{s,i} - t_{thc}} \right| \cdot \Delta \mathrm{m} \quad \text{for all } \mathrm{t_{s,i} \geq t_{thc}}$$

$$HCDM_{th} = \sum \left| t_{s,i} - t_{thh} \right| \cdot \Delta m \quad for\ all\ t_{s,i} \leq t_{thh}$$

When utilizing these equations for the analysis, the smallest number of the results represents the closest to the threshold of the assessment and means that a specimen performed better in terms of thermal comfort.

5.5.3 Analysis of Impact of PCM Positioning on Load Shifting Time

The third analysis stage investigated the impact of PCM positions on peak load shifting. This analysis was based on the comparison of the crossover points of temperatures when changing from cold to warm phases and vice versa during the different experimental cycles. The recorded time was considered an indicator for the amount of peak-hour shifting that could be achieved for a given assembly. The underlying assumption is that any capacity to capture internal thermal loads during heating or cooling processes and shifting them to off-peak time could contribute to energy savings, either through short term changes in climatic boundary conditions at the shifted time (e.g., use of economizers), or alternative grid demand and generation cost. The analysis used an arithmetical and graphical assessment method through scaled result diagrams to evaluate the ability of latent heat storage in different positions to shift peak loads to off time periods and to discuss notable savings potential.

The interior surface temperature used in all experiments to indicate the differences between PCM positions on energy savings by using a metric for load shifting time (LST). This metric (included below for reference) was explained in detail earlier in the section on evaluation criteria to characterize a PCM's influence on energy savings:

$$\mathrm{LST} = \left(\mathrm{T_{EPts,i}}\right) - \left(\mathrm{T_{EPte}}\right) \quad \text{at } \mathrm{EP_{ts,i}} \text{ and } \mathrm{EP_{te}} = \mathrm{T_{Avg\ ts,i}}$$

6 RESULTS AND DISCUSSION

Overall, the results of the experiments confirmed the latent changes by analyzing the delay in temperature changes of the specimen profiles in different positions with varying numbers of layers that were expected when utilizing PCMs in comparison to no insulation. In this section, the result and discussion for the configurations P1X1, P1X3, P2X1, and P2X3 are individually discussed. The discussion for each configuration is based on the previously described stages. At the end of this section, a comparison between results of these configurations will be shown to demonstrate the impact of PCM positioning on thermal comfort and load shifting time.

6.1 FINDINGS OF P1X1 CONFIGURATION: 1 LAYER OF PCM AND 1 LAYER OF XPS

6.1.1 P1X1: DIFFERENTIAL RESULT PATTERNS OF PCMS IN DIFFERENT POSITIONS

There were several observations made in the first analysis stage that utilized graphical methods for a comparison of the recorded results. A graphic overlay of all experiments confirmed that the results showed reasonable repeatability of the PCM's behavior in each position during the various solidifying and melting phases with consistent performance in each cycle. Similarly, the PCM specimens showed the same behavior under repeated tests.

In terms of temperature differences over time, it was observed that when the PCM was placed on the exterior side of the cavity (EP), the temperature differences between the interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM were more pronounced than when placed on the interior side (IP) of the cavity—especially during the cooling processes. For the EP experiments, the melting and freezing process are clearly visible when the temperature difference widens and becomes larger than the standard proportional difference of the material's thermal resistance.

Furthermore, when the PCM was utilized in the exterior position (EP) of the wall, it reacted faster and reached its steady state in both cycles in around 2 hours and 20 minutes. In contrast, when the PCM was utilized in the interior position (IP), it reached a steady state condition in each phase after 4-6 hours. In both positions, the PCM activated its thermal storage capacity, but its performance during the freezing phase was slightly better than its performance during the melting cycle. Also, the temperature difference between $t_{pcm,e}$ and $t_{pcm,i}$ in EP was similar to IP. Figure (45) shows the comparison of PCM behavior during exterior (EP) and interior (IP) cavity placement in P1X1 configuration.

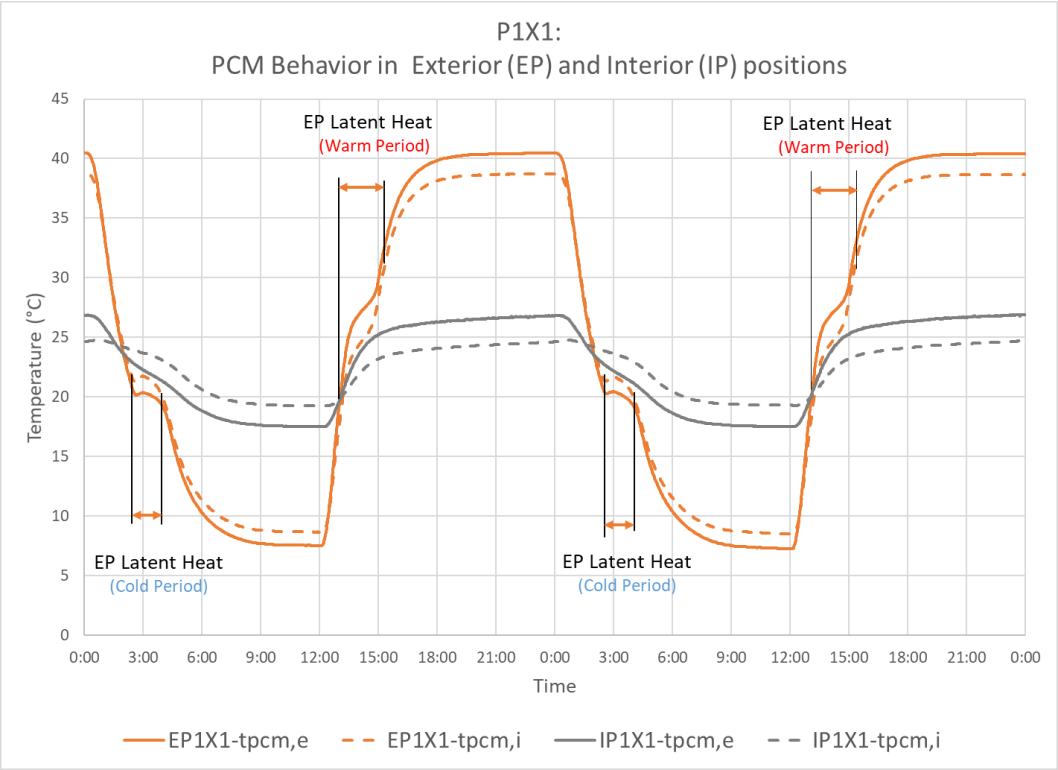


Figure (45) P1X1: Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement.

6.1.2 P1X1: Analysis of PCM Positioning Impact on Thermal Comfort

This stage of the study analyzed the measured temperatures of the experiments in terms of their effect on thermal comfort. For this evaluation, measured interior surface temperatures were utilized as contributing metrics towards broader comfort considerations. Figure (46) shows a comparative distribution of the measured surface temperatures of all specimen types for 3 days. The findings of day 2 was inconclusive, so day 2 was excluded from the analysis of this configuration. Day 3 was selected for the analysis since the results for all specimens' positions were within the boundary condition of interior temperature.

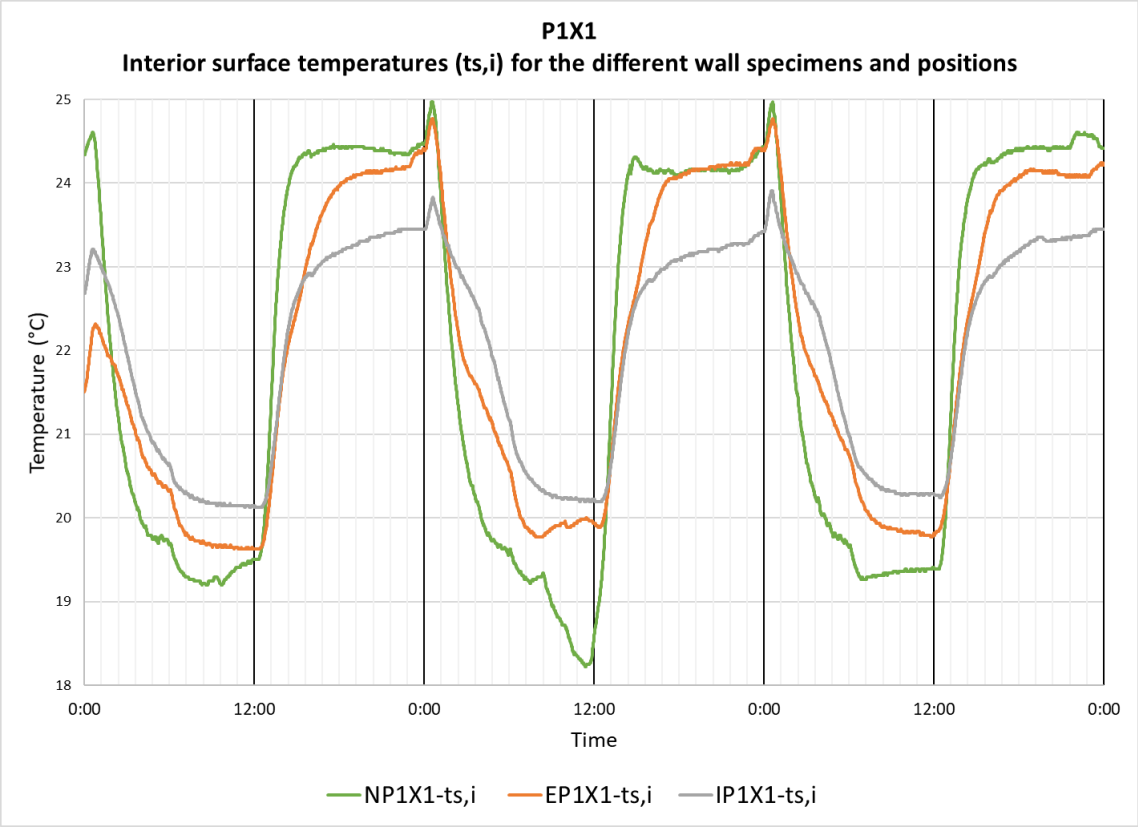


Figure (46) P1X1: Interior surface temperatures ($t_{s,i}$) for all wall specimens.

The impact on comfort was assessed through calculating a specific metric that was developed for this study and termed Comfort Degree Minutes (CDM), as it captures temperature differences between interior surface temperature ($t_{s,i}$) and its offset from the interior setpoint or threshold temperature. The CDM metric was used to determine both cooling comfort degree minutes (CCDM) and heating comfort degree minutes (HCDM). Figure (47) and Figure (48) illustrate this method graphically, where the area between $t_{s,i}$ and the cut-off threshold temperature represents the CDM value.

The thermal comfort has been calculated for the cold period as shown in Table (6) and for the warm period as shown in Table (7). The CDM for the different specimens during both cold and warm periods were calculated for day 3 as follows:

Table (6) P1X1: CCDM when switching to a cold climate.

P1X1: Cooling Comfort Degree Minutes (CCDM)			
Day 3	**NP**	**EP**	**IP**
CCDM – 22.5	1652	1130	856

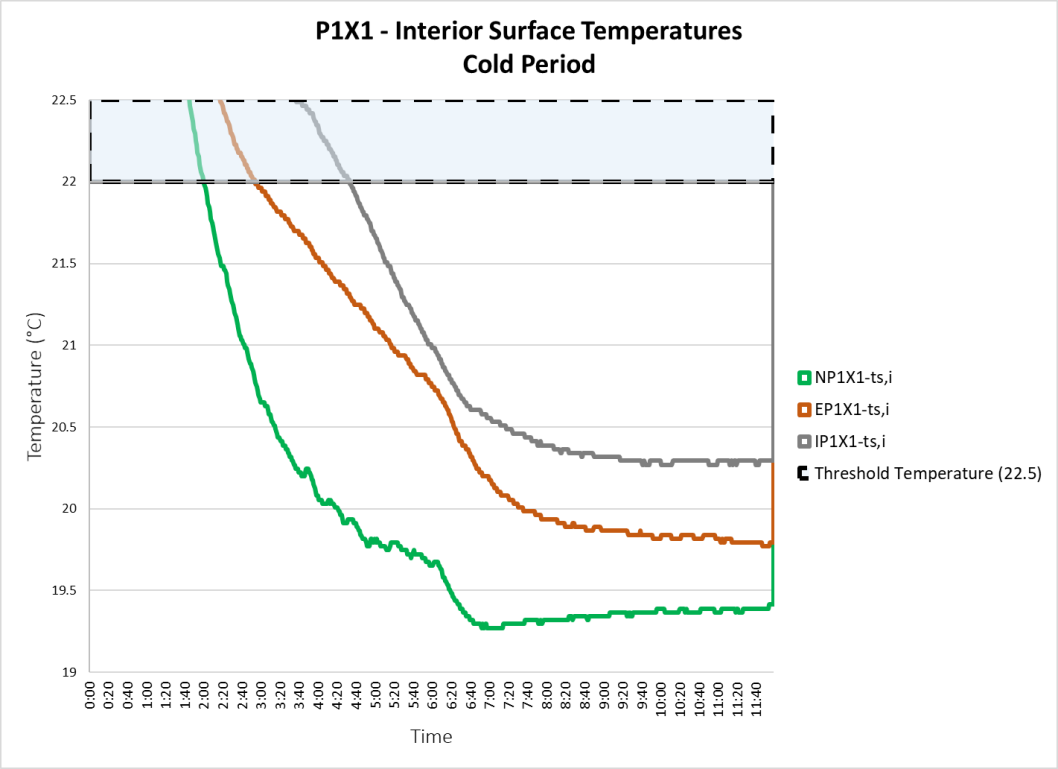


Figure (47) P1X1: Visualization assessment of CDM-cold period.

Table (7) P1X1: HCDM when switching to a hot climate.

P1X1: Heating Comfort Degree Minutes (HCDM)			
Day 3	**NP**	**EP**	**IP**
HCDM – 22.5	1123	807	386

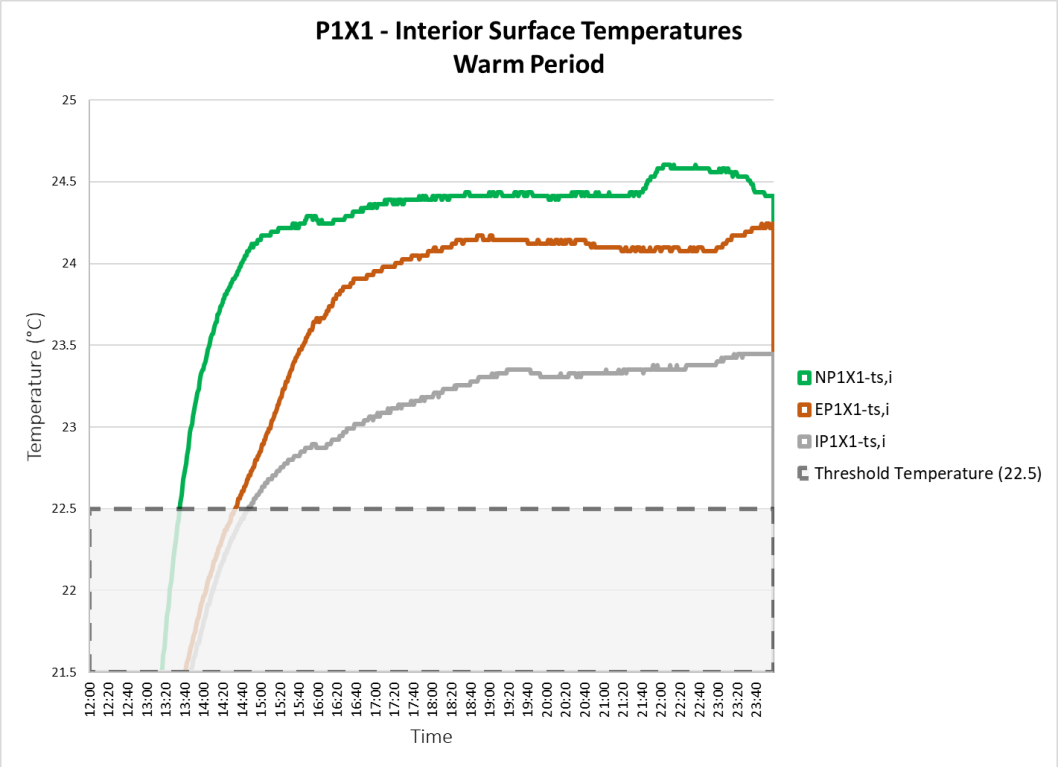


Figure (48) P1X1: Visualization assessment of CDM-warm period.

The results of these assessments illustrate that specimen NP shows the largest number of CDM. Specimen IP shows the smallest number of CDM, with specimen EP in the middle for both periods for cold and hot climates. The smallest number represent the closest to the threshold of the assessment. While a difference was observed between the two PCM positions EP and IP, a more notable difference can be observed for the specimen without PCM (NP). For instance, in hot climates, the specimen IP was closer than EP to the threshold. These results indicate a slight advantage for PCMs in the interior position of the cavity in this configuration (P1X1:1-layer of PCM and 1-layer of XPS).

6.1.3 P1X1: Analysis of PCM Positioning Impact on Load Shifting Time

This stage investigated the impact of PCM positions on peak load shifting time (LST). Moreover, the LTS metric has been used to calculate load shifting time in this research. The assessment of LST depends on the crossing time between the exterior temperature and the interior surface temperature and the average surface temperatures of all position of the specimens. A comparative analysis of the P1X1 configuration has been used to demonstrate the effects of different positions

of PCM, different amounts of PCM, and different thicknesses of XPS integrated with PCM on thermal performance in building enclosures.

Figure (49) shows the load shifting time of all specimens that were used in the P1X1 configuration with the exterior temperature (t_e) and Figure (50) shows the range of interior surface temperature ($t_{s,i}$) for wall specimens. EP and IP specimens show significant lag times when shifting from the warm to cold exterior climate periods. As previously mentioned, when switching to the warm period, the effect becomes less visible and the differences are less pronounced between the two PCM positions. In both scenarios it can be observed how the temperatures of the interior surface ($t_{s,i}$) starts merging again as the phase change effect wanes off.

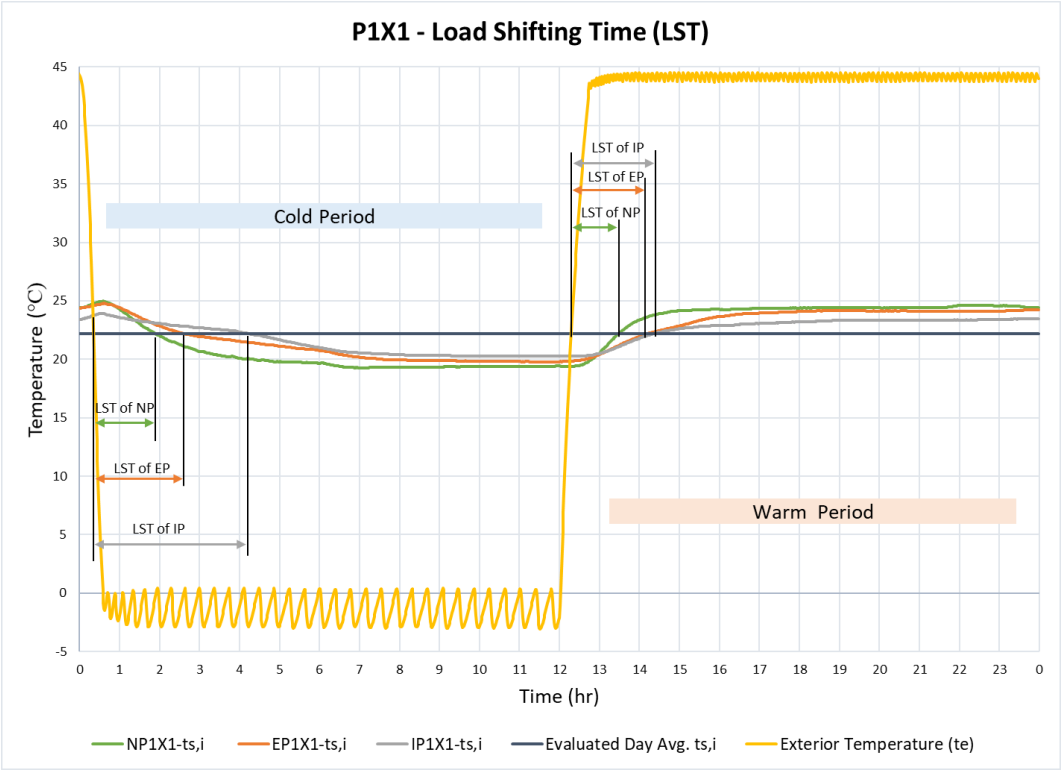


Figure (49) P1X1: Load shifting time with exterior temperature (t_e).

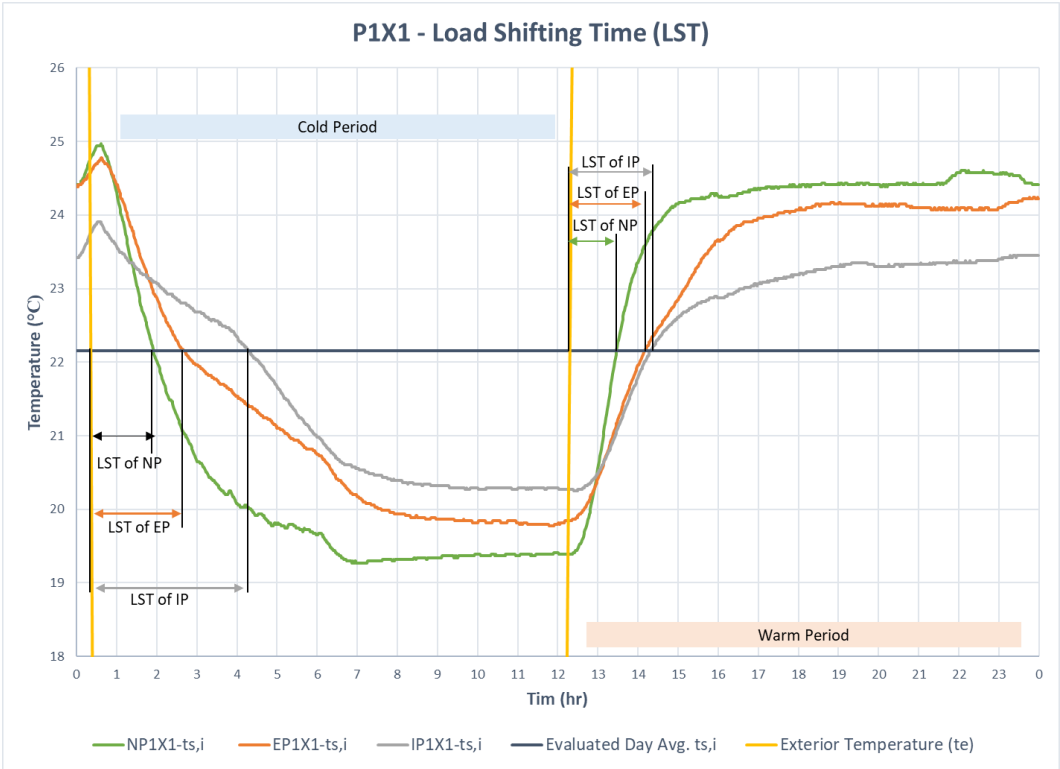


Figure (50) P1X1: Load shifting time (the range of interior surface temperature ($t_{s,i}$) for wall specimens).

Figure (51) illustrates the load shifting time in hours for all specimens in the P1X1 configuration. The shifting time has been calculated from the crossing time between exterior temperature and the average temperature of the interior surface for the three specimens. However, the IP specimen achieved a slightly bigger lag of almost 4 hours, while the specimen in EP position only achieved around 2 hours and 20 minutes in the warm period.

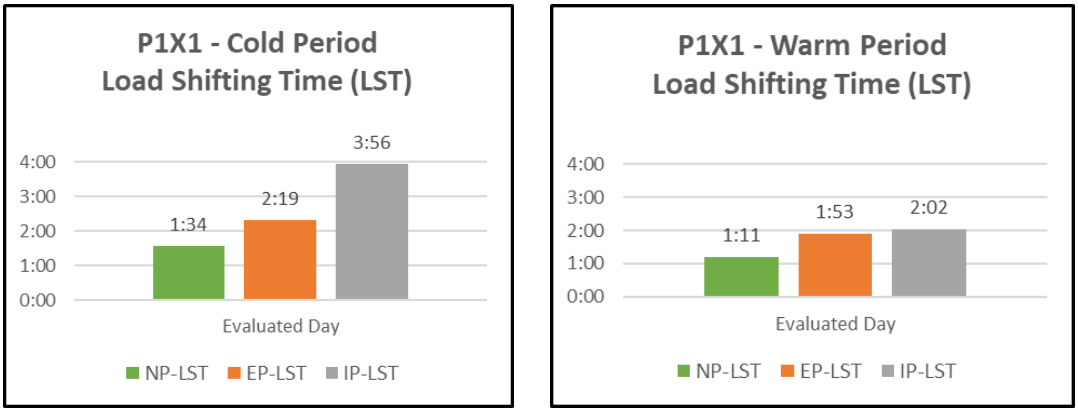


Figure (51) P1X1: Load shifting time in cold and warm periods.

6.2 Findings of P1X3 Configuration: 1 layer of PCM and 3 layers of XPS

6.2.1 P1X3: Differential Result Patterns of PCMs in Different Positions

By using graphical methods to compare the recorded results, several observations of the PCM's behavior in EP and IP positioning can be made. Experiments confirmed that the results show reasonable repeatability of the PCM's behavior in each position during the various solidifying and melting phases with consistent performance in each cycle.

During experimental time, when the PCM was placed on the exterior side of the cavity (EP), a super cooling occurred after 4 hours of cooling time. Also, the charging time was longer on the cooling time for the same specimen. The temperature differences between the interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM were similar for both positions in warm and cold periods. In both positions, the PCM activated its thermal storage capacity, but its performance during the melting phase was slightly better overall than its performance during the cooling process, as shown in Figure (52).

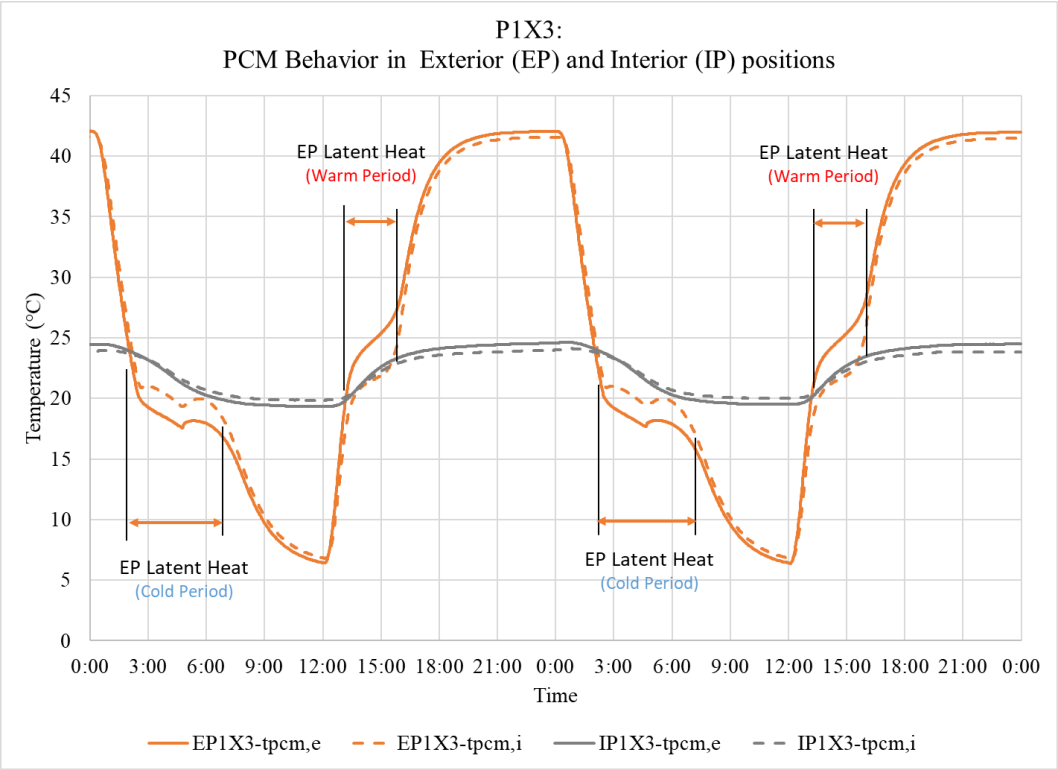


Figure (52) P1X3: Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement.

6.2.2 P1X3: Analysis of PCM Positioning Impact on Thermal Comfort

For this configuration, the study analyzed the measured temperatures of the experiments in terms of their effect on thermal comfort. Like what has been done for the previous configuration, measuring interior surface temperatures was utilized as contributing metrics to inclusive comfort considerations in this analysis. Figure (53) shows a comparative distribution of the measured surface temperatures of all specimen types for 3 days. The findings of day 2 was inconclusive, but day 3 was more identical for all specimens' positions and therefore was selected for the analysis of this configuration.

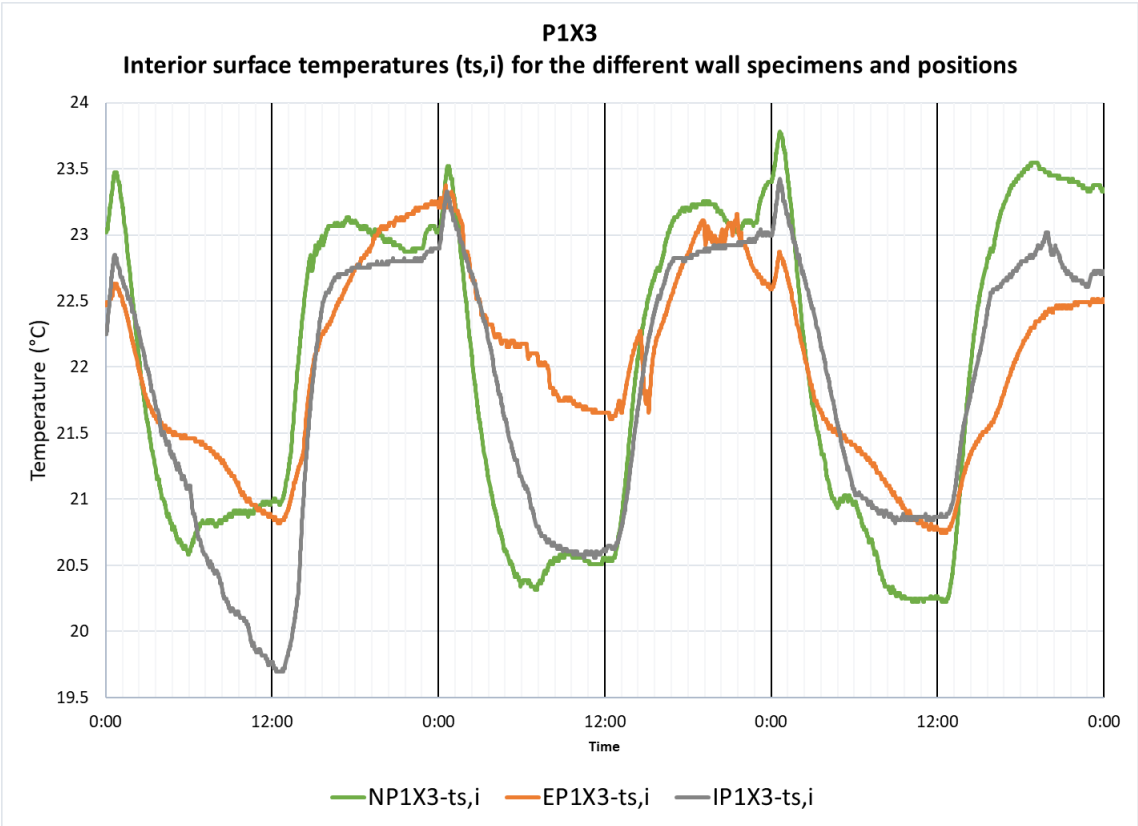


Figure (53) P1X3: Interior surface temperatures ($t_{s,i}$) for all wall specimens.

The analysis of thermal comfort of this configuration used the same steps of the previous configuration. The impact on comfort was assessed through calculating the CDM metric. The following figures illustrate the graphically findings for this configuration. The thermal comfort has been calculated for cold climate as shown in Table (8) and Figure (54) and hot climate is shown in Table (9) and Figure (55). The comfort degree minutes for the different specimen in both cold and warm phases were calculated for day 3 as follows:

Table (8) P1X3: CCDM when switching to a cold climate.

P1X3: Cooling Comfort Degree Minutes (CCDM)			
Day 3	**NP**	**EP**	**IP**
CCDM – 22.5	1013	724	714

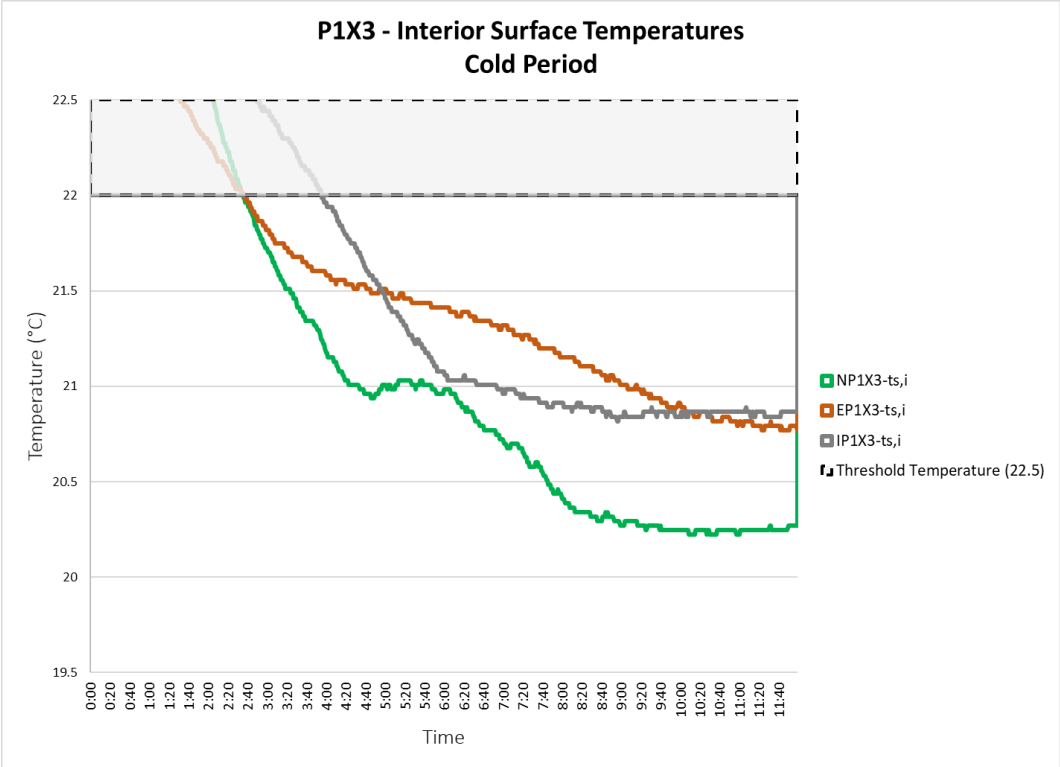


Figure (54) P1X3: Visualization assessment of CDM-cold period.

Table (9) P1X3: HCDM when switching to a hot climate.

P1X3: Heating Comfort Degree Minutes (HCDM)			
Day 3	**NP**	**EP**	**IP**
HCDM – 22.5	440	0	122

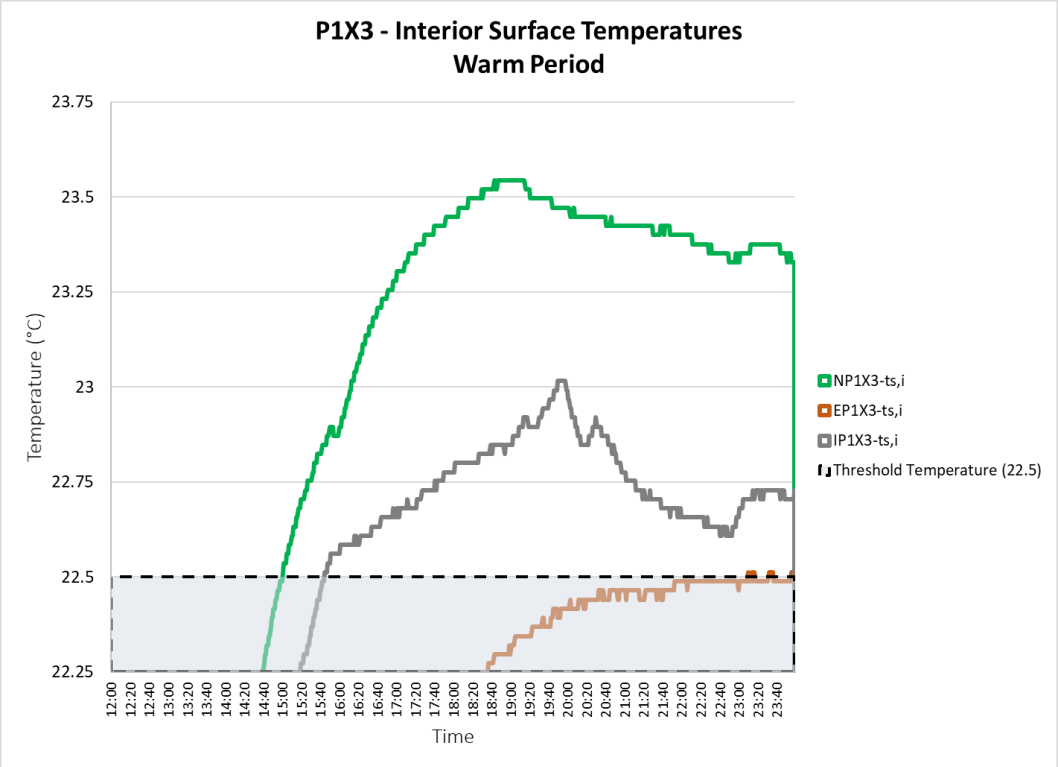


Figure (55) P1X3: Visualization assessment of CDM-warm period.

The results of these assessments illustrate that specimen NP shows the largest number of CDM during both periods. For the cold period, EP and IP were close to each other, although the IP performed better for thermal comfort from the beginning of the period and was closer to the threshold. During the cold period, the EP specimen showed the smallest number of CDM, followed by specimen IP in both cycles for cold and hot climates. The smallest number represent the closest to the threshold for the assessment. During the cooling processes, the EP specimen did not exceed the threshold and stayed within the range of the cooling refence point and threshold. A difference was observed between the two PCM positions EP and IP, while again a more notable difference can be observed for the specimen without PCM (NP). These results indicate a slight advantage for PCMs in the interior position of the cavity in hot climates and a significant advantage for PCMs in the exterior position of the cavity in cold climate of the P1X3 configuration (1-layer of PCM and 3-layers of XPS).

6.2.3 P1X3: Analysis of PCM Positioning Impact on Load Shifting Time

This stage investigated the impact of PCM positions on peak load shifting for the P1X3 configuration. In this configuration, the assessment of LST used the same strategy that was used in the previous configuration. By using the LTS metric, the calculation of load shifting time can be shown for a comparative analysis. The results demonstrate the effects of different positions of PCM, different amounts of PCM, and different thicknesses of XPS integrated with PCM on thermal performance in building enclosures. For this configuration (P1X3), Figure (56) and Figure (57) show all specimens that were used and indicate their effects on load shifting.

In the cold period, the effects of the EP specimen on load shifting is less visible and the there was only a minor difference between EP and NP specimens. In the same period, the IP specimen showed more effect on load shifting than EP. However, during the heating process, it was the reverse. In other words, the EP specimen had a significant impact on load shifting in contrast with IP. The difference between IP an NP was less so.

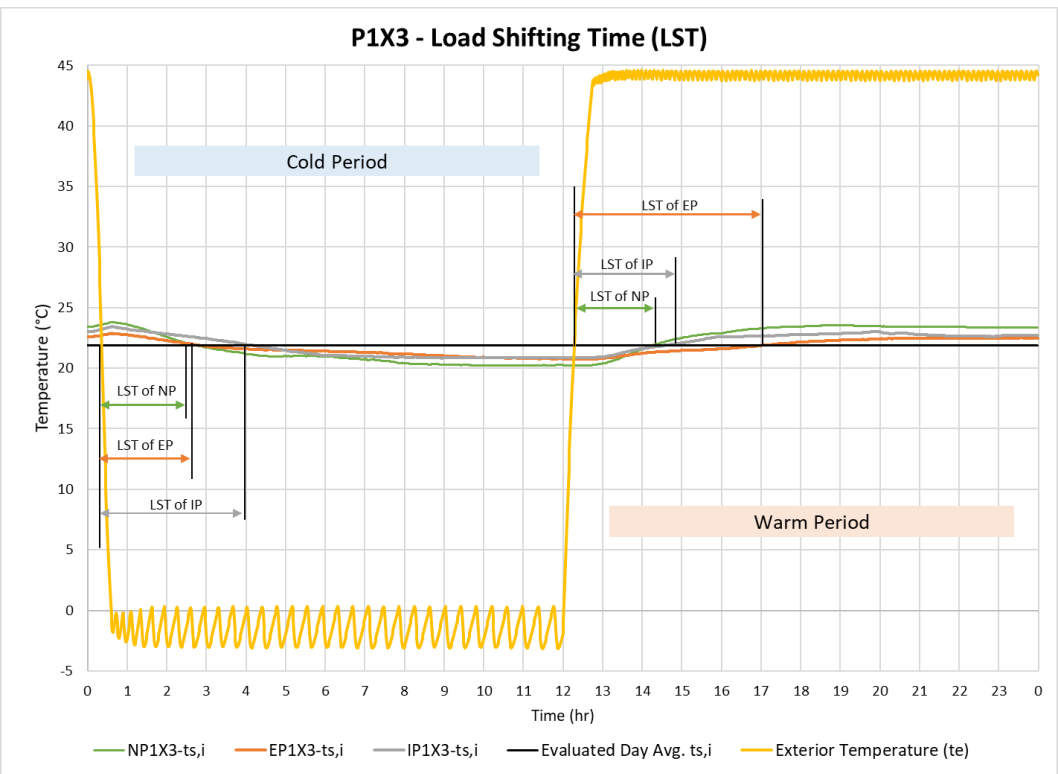


Figure (56) P1X3: Load shifting time with exterior temperature (t_e).

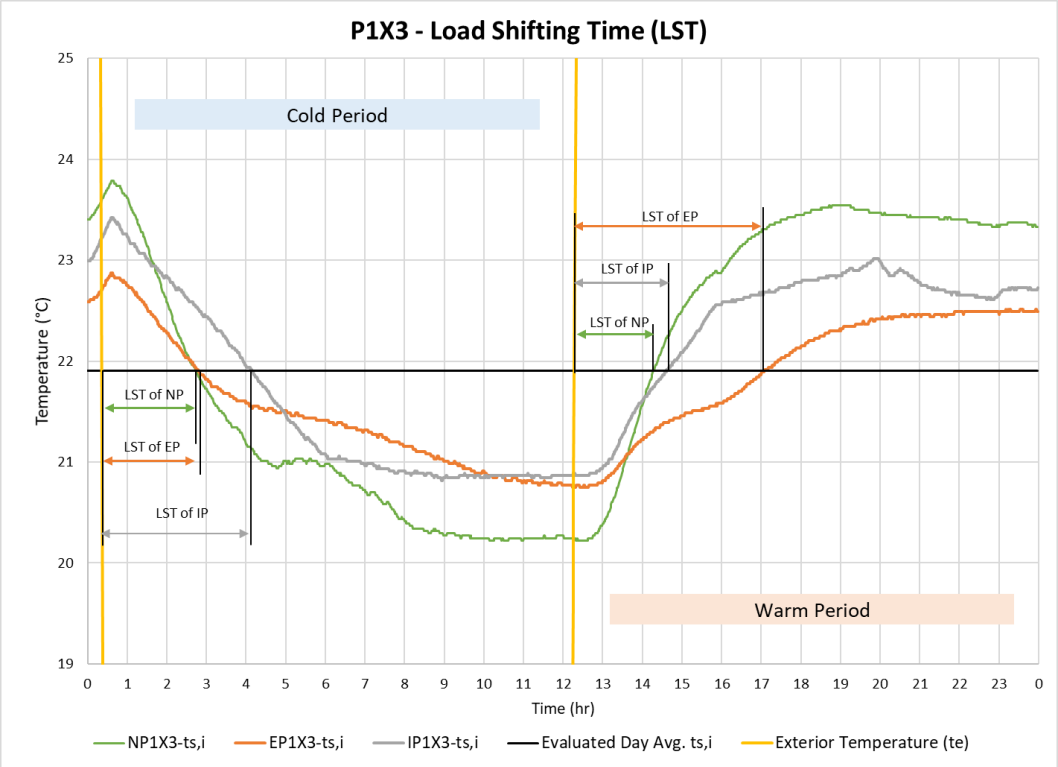


Figure (57) P1X3: Load shifting time (the range of interior surface temperature ($t_{s,i}$) for wall specimens).

Figure (58) demonstrates the differences between all specimens with an indication of measured load shifting time. In the cold periods, IP had almost a 4-hour impact on load shifting, but its effect was less in the heating period. In contrast, EP exhibits the reverse. Its effect on load shifting in the cold period was very minor and had almost the same effect as the NP specimen; however, in the warm period, it had an effect of almost 5 hours on shifting load difference from the baseline of the assessment.

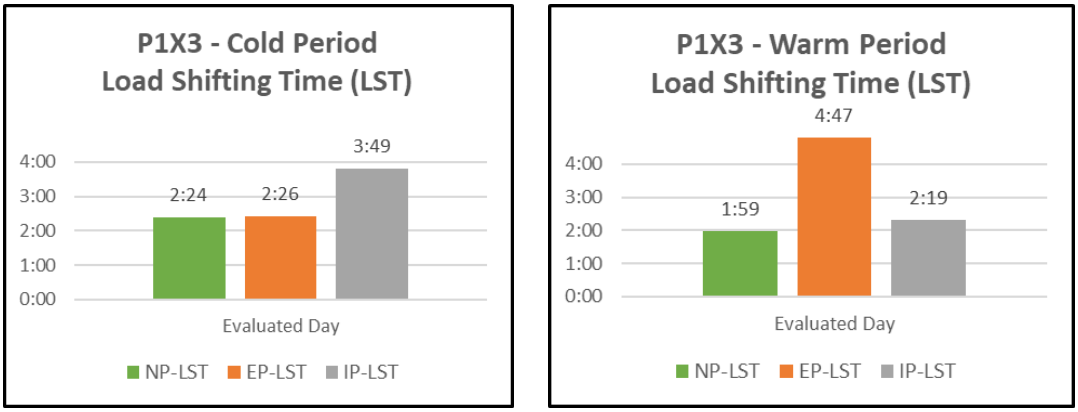


Figure (58) P1X3: Load shifting time in cold and hot periods.

6.3 Findings of P2X1 Configuration: 2 layers of PCM and 1 layer of XPS

6.3.1 P2X1: Differential Result Patterns of PCMs in Different Positions

In the P2X1 configuration, the PCM's behavior in the EP and IP positioning was recorded and graphical methods of comparison were used to make several observations. Figure (59) shows the PCM's behavior in cold and warm periods for day 2 and 3. The results of the experiments represent the effected changes of the PCM in EP and IP positions and confirm the reasonable repeatability of the PCM's behavior during the various solidifying and melting phases in each cycle with consistent performance. The PCM in the EP position had almost equal time for charging and discharging during both cycles of the experiment. Also, a super cooling occurred for the PCM in EP after 3 hours of cooling time. The temperature differences between the interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM were similar for both positions in warm and cold periods. In both positions, the PCM activated its thermal storage capacity, but its performance during the melting phase was slightly better than its performance during the cooling process.

Moreover, when the PCM was utilized in the exterior position (EP) of the wall, it reacted and reached its steady state in the heating period, but in the cold period it did not. In contrast, when the PCM was utilized in the interior position (IP), it did not reach a steady state condition in either period.

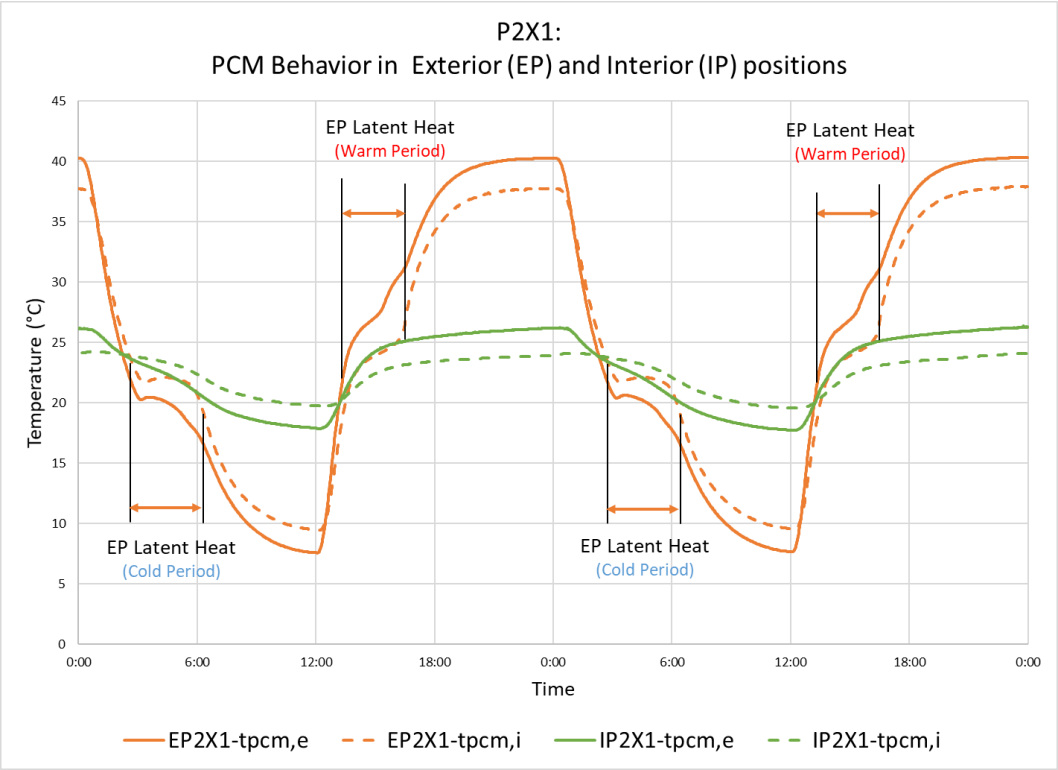


Figure (59) P2X1: Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement.

6.3.2 P2X1: Analysis of PCM Positioning Impact on Thermal Comfort

Similar to the analyses that were carried out for the previous configurations, the measured temperatures of the P2X1 configuration have been recorded to analyze the effect of different positions on thermal comfort. Measuring interior surface temperatures was utilized with the CDM metric to make inclusive comfort considerations in this analysis. A comparative distribution of the measured surface temperatures of all specimen types for 3 days are shown in Figure (60). When comparing these days in terms of homogeneous changes, the (t_i) of the specimen without PCM (NP) in day 3 was out of the boundary condition and it was excluded from the analysis. Day 2 was more identical for all specimens' positions and was therefore selected for the analysis of this configuration.

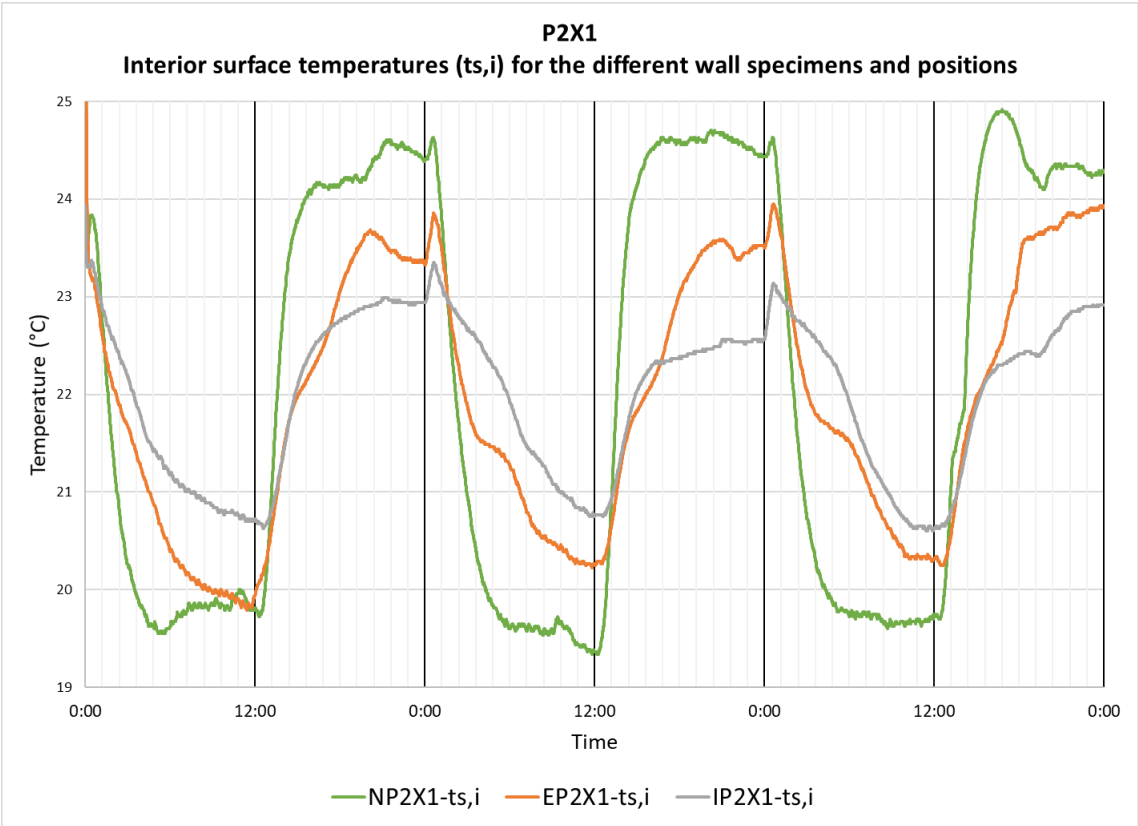


Figure (60) P2X1: Interior surface temperatures ($t_{s,i}$) for all wall specimens.

The analysis of thermal comfort of this configuration used the same steps of the previous configuration. The impact on thermal comfort was assessed through calculating the CDM metric. The graphical findings of this configuration are illustrated in Figure (61) for the cold period and in Figure (62) for the warm period. Also, the results of the arithmetic calculation for the thermal comfort for the cold period are shown in Table (10) and the results of the warm period are shown in Table (11). The Comfort Degree Minutes for the different specimen in both cold and warm periods were calculated for day 2 as follows:

Table (10) P2X1: CCDM when switching to a cold climate.

P2X1: Cooling Comfort Degree Minutes (CCDM)			
Day 2	**NP**	**EP**	**IP**
CCDM – 22.5	1554	894	505

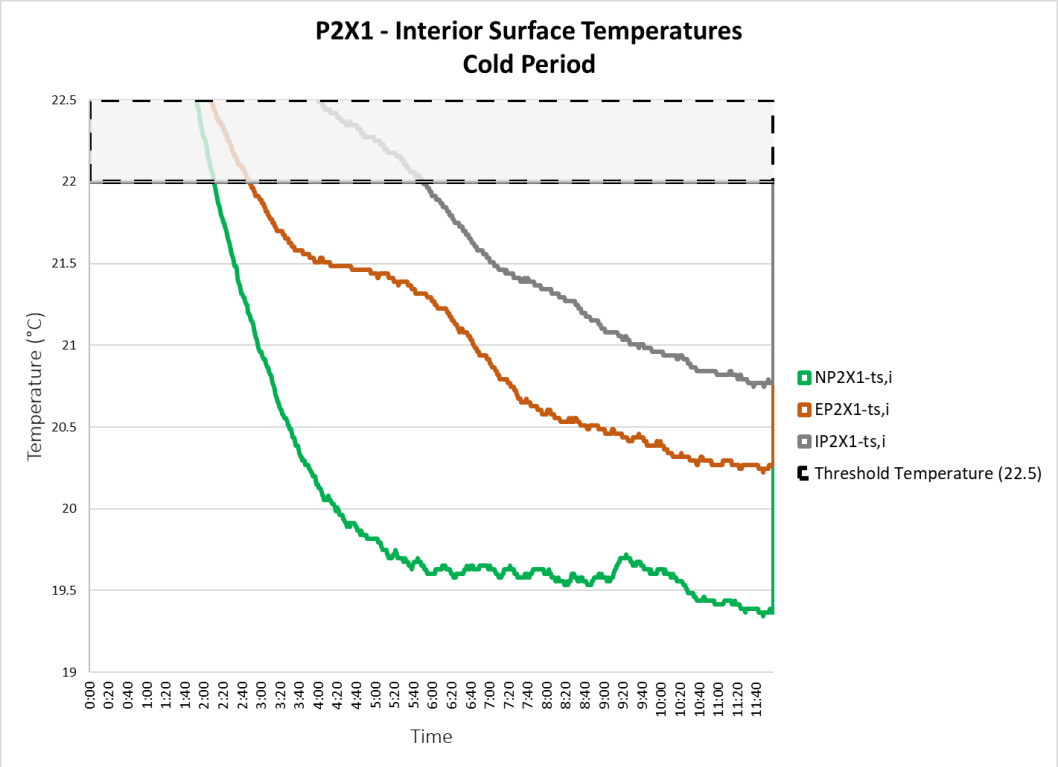


Figure (61) P2X1: Visualization assessment of CDM-cold period.

Table (11) P2X1: HCDM when switching to a hot climate.

P2X1: Heating Comfort Degree Minutes (HCDM)			
Day 2	**NP**	**EP**	**IP**
HCDM – 22.5	1191	353	9

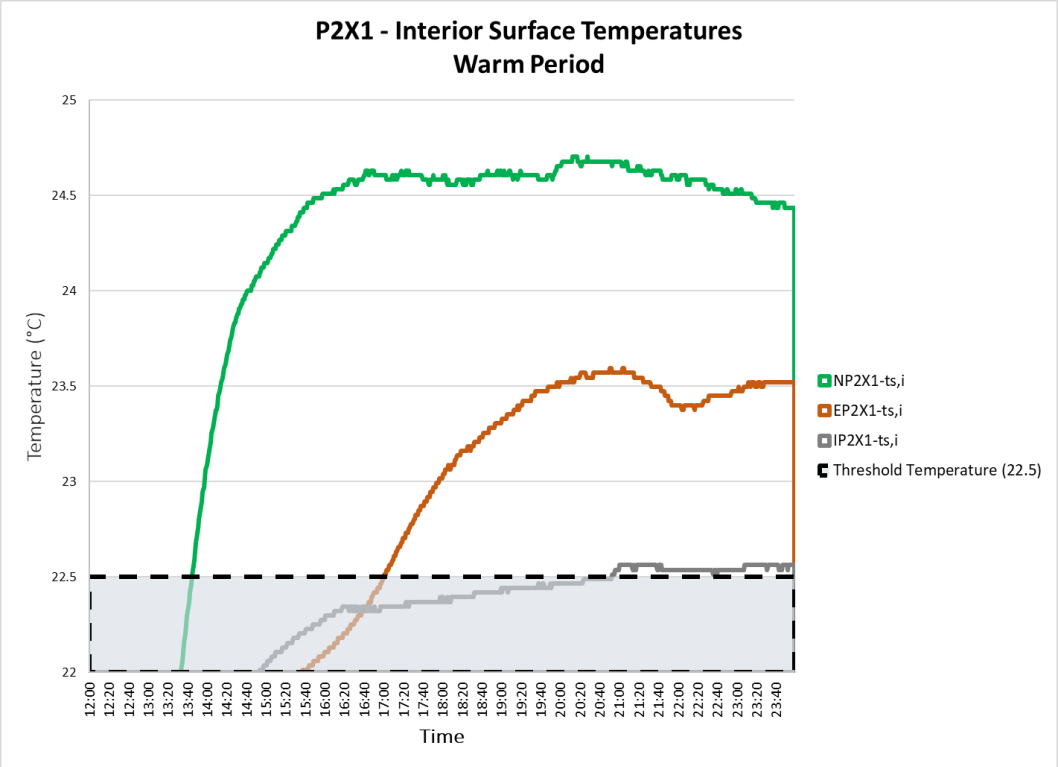


Figure (62) P2X1: Visualization assessment of CDM-warm period.

The results of these assessments illustrate that the NP specimen showed the largest number of CDM in both periods. For the cold period, the IP specimen performed better for thermal comfort and the difference between IP and EP specimens is notable. During the cold period, the IP specimen performed even better, and it was almost within the range of threshold during this entire period. Moreover, when comparing all specimens, the IP specimen showed the smallest number of CDM. A minor difference was observed between the two PCM positions EP and IP, while again a more notable difference can be observed for the specimen without PCM (NP). In this configuration, the IP specimen performed better than the EP specimen in all climate scenarios. These results indicate a slight advantage for PCMs in the interior position of the cavity in cold climate and a significant advantage for PCMs in the interior position of the cavity in warm climate of the P2X1 configuration (2-layers of PCM and 1-layer of XPS).

6.3.3 P2X1: Analysis of PCM Positioning Impact on Load Shifting Time

In this configuration, the effects of PCM positioning on load shifting time were analyzed by graphical method, and the assessment of LST was accomplished by using the same strategy that

was used for the previous configurations. Figure (63) and Figure (64) show the results for all specimens and indicate their effects on load shifting.

In the cold period, the IP specimen showed more effects on load shifting than the EP specimen. Also, in the same period, the EP specimen's effect was close to the NP specimen and the differences between them was only about 30 minutes. In the warm period, the IP specimen and the EP specimen had a significant impact on load shifting, but the IP specimen had a longer effect of an additional 50 minutes.

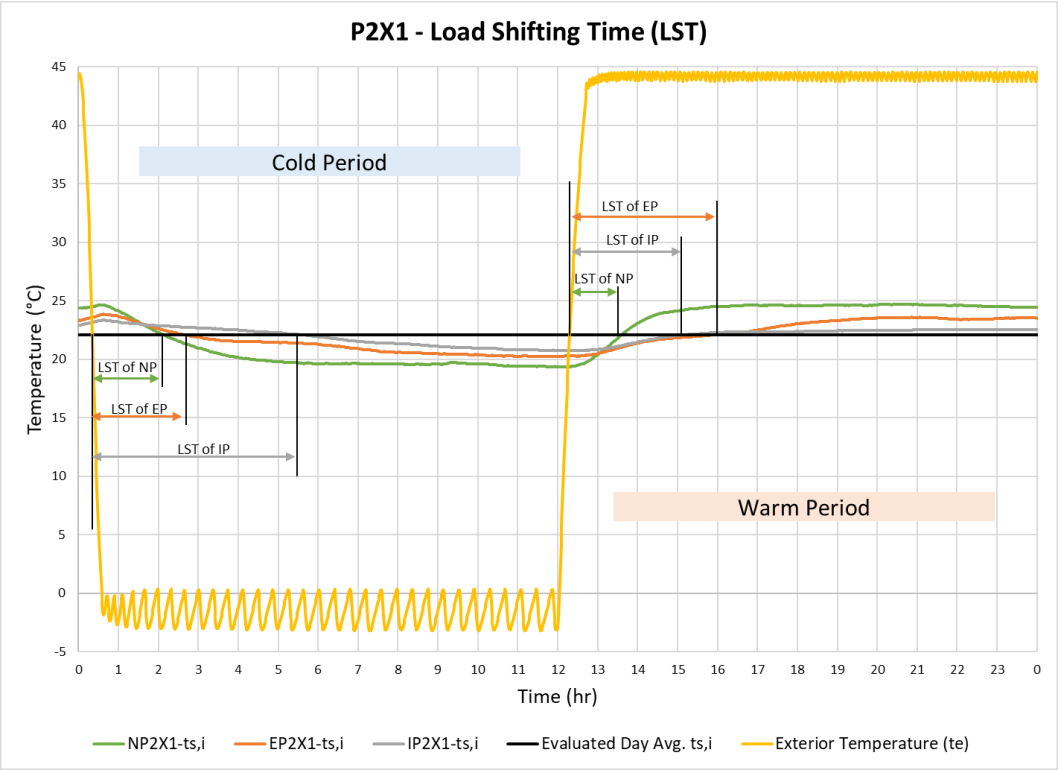


Figure (63) P2X1: Load shifting time with exterior temperature (t_e).

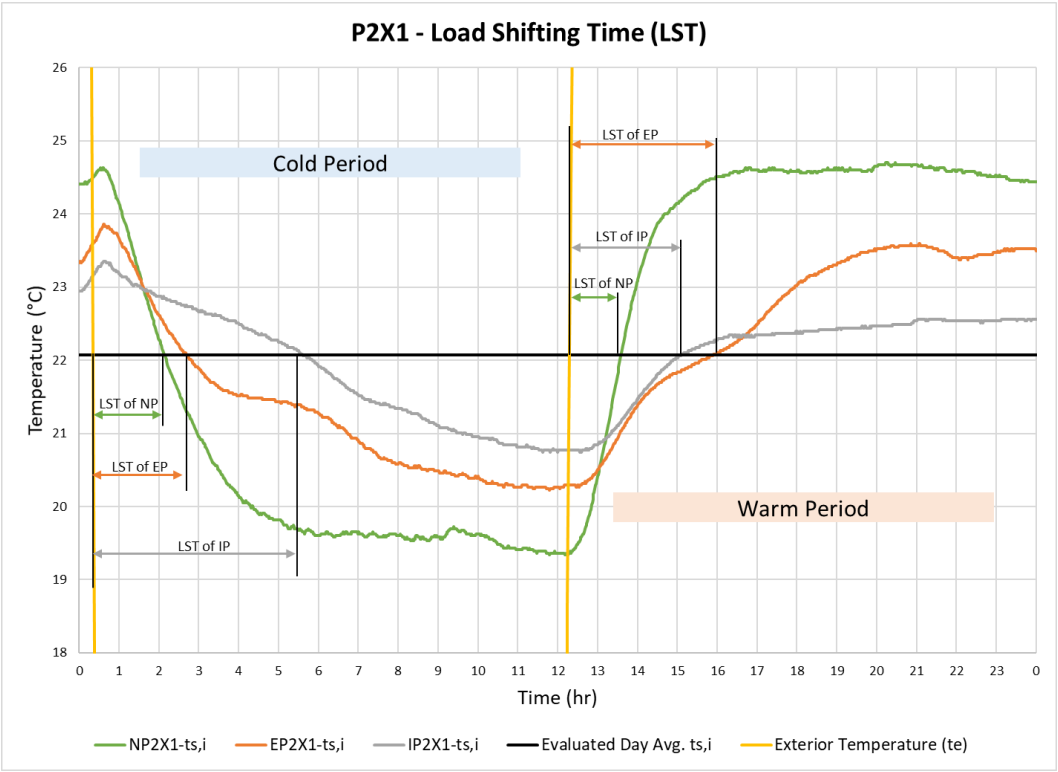


Figure (64) P2X1: Load shifting time (the range of interior surface temperature ($t_{s,i}$) for wall specimens).

The LTS metric was used to calculate load shifting time in the P2X1 configuration and Figure (65) shows the results for a comparative analysis. The results demonstrate the effects of each specimen on load shifting time in cold and warm periods. In comparing these results, it can be seen that the IP specimen experienced longer load shifting by 5 hours and 15 minutes during the cooling process, but the effect during the heating process was less. On the other hand, the EP specimen showed the reverse effect in both periods. In other words, it had less effect on load shifting time in the cold period and a significant effect during the heating process by an additional 3 hours and 40 minutes of load shifting time.

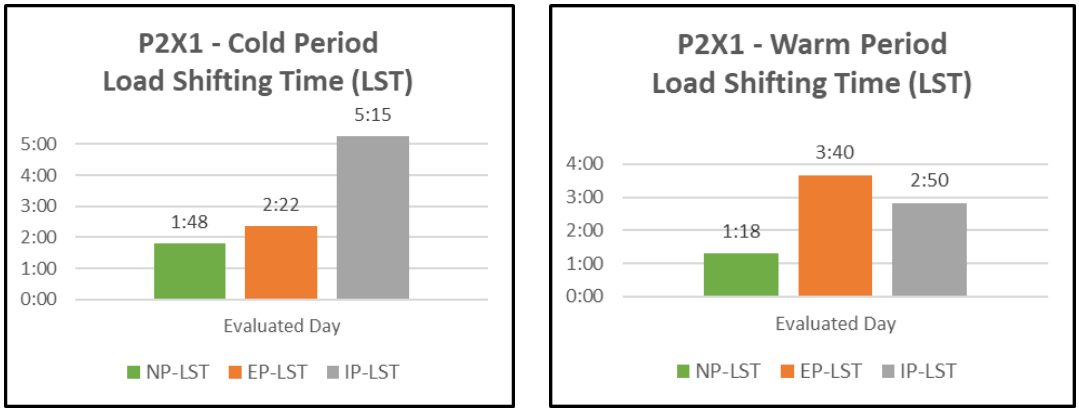


Figure (65) P2X1: Load shifting time in cold and warm periods.

6.4 Findings of P2X3 Configuration: 2 layers of PCM and 3 layers of XPS

6.4.1 P2X3: Differential Result Patterns of PCMs in Different Positions

The analysis of this configuration follows the same steps that were used for the prior configurations. Graphical methods of comparison were used to make several observations from recorded PCM behavior in EP and IP positions. Figure (66) shows the PCM's behavior in cold and warm periods for day 2 and 3. The results of the experiments presented the changes in PCM in the EP and IP position and confirmed the reasonable repeatability of the PCM's behavior during several solidifying and melting phases in each cycle with consistent performance. The PCM in the EP position experienced almost equal time for charging and discharging during both cycles of experiments. Also, a super cooling occurred for the PCM in EP after 3 hours of cooling time. The temperature differences between the interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM in the EP position were larger than the differences in the IP position.

Furthermore, when the PCM was utilized in the exterior position (EP), it reacted faster and reached its steady state in the warm period only. In contrast, when the PCM was utilized in the interior position (IP), it reached a steady state condition in each phase after 5-7 hours. In both positions, the PCM activated its thermal storage capacity, but its performance during the melting phase was slightly better than its performance during the cold period. For the EP experiments, the melting and freezing periods are clearly visible when the temperature difference widens and becomes larger than the standard proportional difference of the material's thermal resistance.

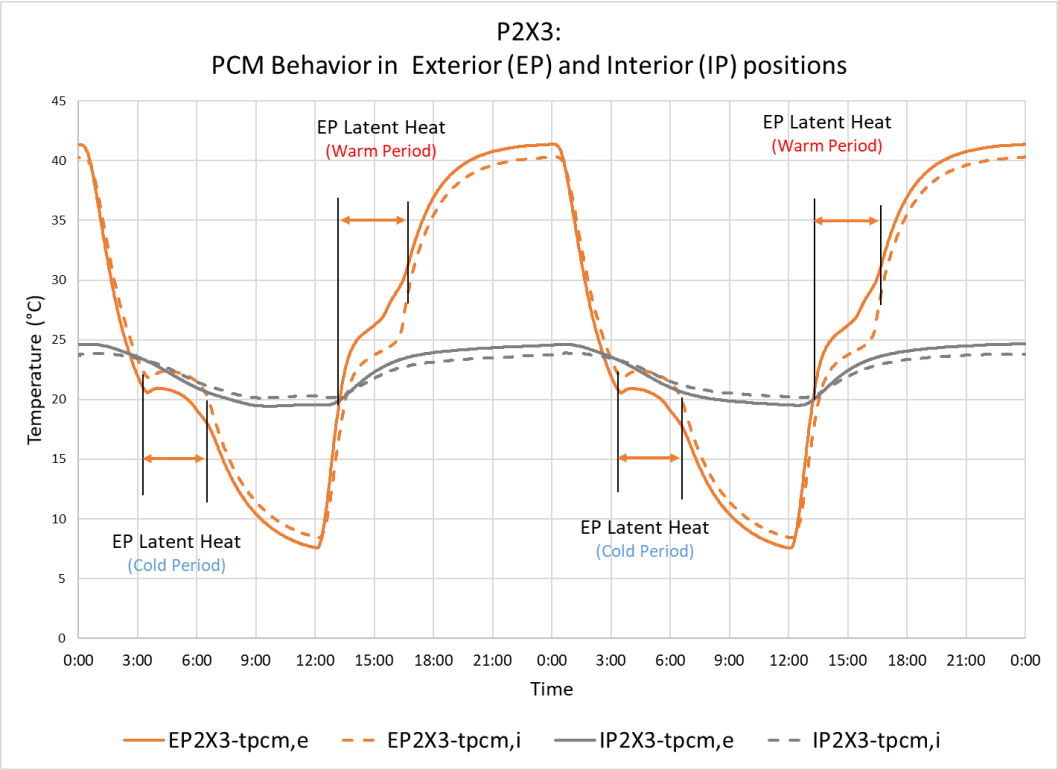


Figure (66) P2X3: Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement.

6.4.2 P2X3: Analysis of PCM Positioning Impact on Thermal Comfort

For the P2X3 configuration, the analyses follow the same steps as the previous configurations. The measured temperatures of this configuration have been recorded to analyze the effect of different positions on thermal comfort. Measuring interior surface temperatures was utilized with the CDM metric for inclusive comfort considerations.

A comparative distribution of the measured surface temperatures of all specimen types for 3 days in different positions are shown in Figure (67). When comparing these days in terms of homogeneous changes, in day 2, (t_i) was out of the range during IP test, so day 2 was excluded from the analysis. Also, day 3 was more identical for all specimens' positions and was therefore selected for the analysis of this configuration.

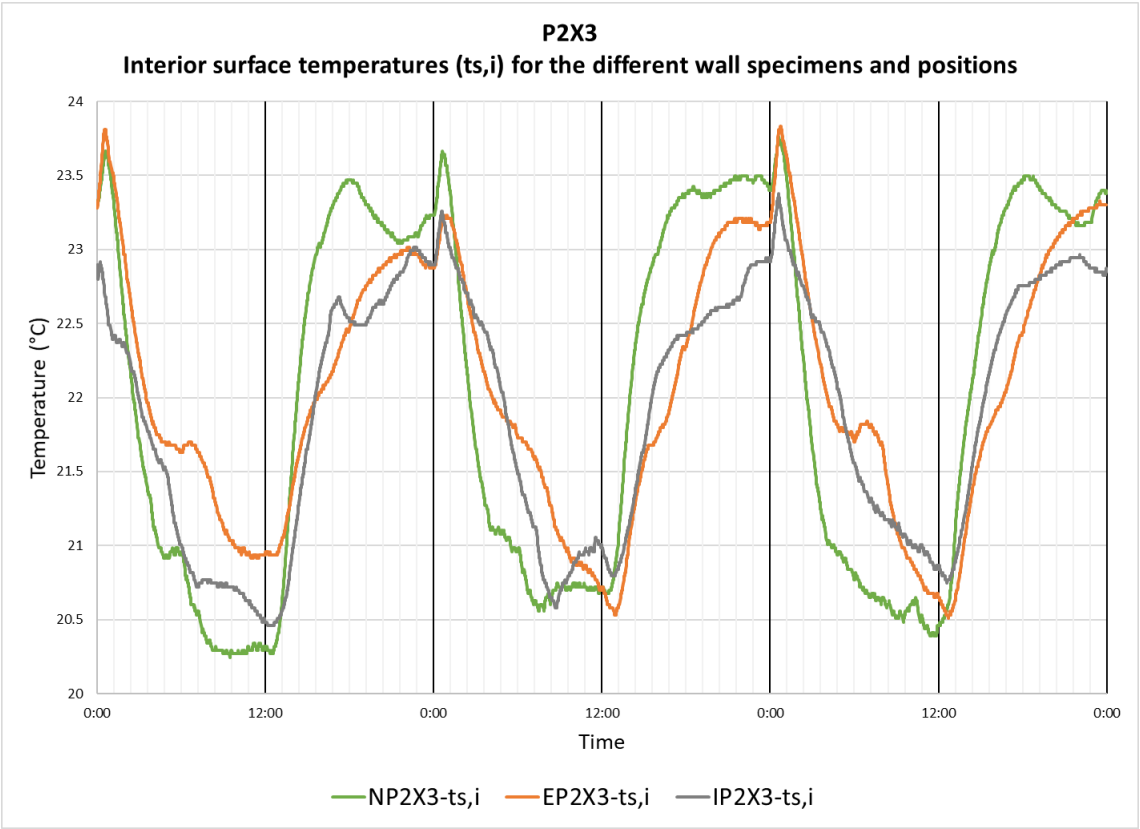


Figure (67) P2X3: Interior surface temperatures ($t_{s,i}$) for all wall specimens.

The analysis of thermal comfort for this configuration used the same steps as the previous configurations. The impact on thermal comfort was assessed through calculating the CDM metric. The graphical findings of this configuration are illustrated in Figure (68) for the cold period and Figure (69) for the warm period. Also, the results of the arithmetic calculation for the thermal comfort during the cold period are shown in Table (12) and the results of the warm period in Table (13). As the day 3 results were more similar between all specimens, the CDM for the different specimens in both cold and warm period were calculated for day 3 as follows:

Table (12) P2X3: CCDM when switching to a cold climate.

P2X3: Cooling Comfort Degree Minutes (CCDM)			
Day 3	**NP**	**EP**	**IP**
CCDM – 22.5	970	551	556

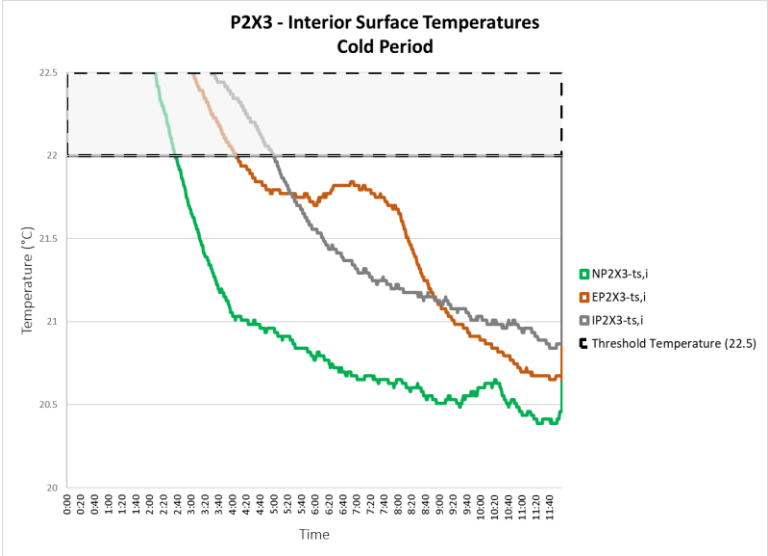


Figure (68) P2X3: Visualization assessment of CDM-cold period.

Table (13) P2X3: HCDM when switching to a hot climate.

P2X3: Heating Comfort Degree Minutes (HCDM)			
Day 3	**NP**	**EP**	**IP**
HCDM – 22.5	406	200	144

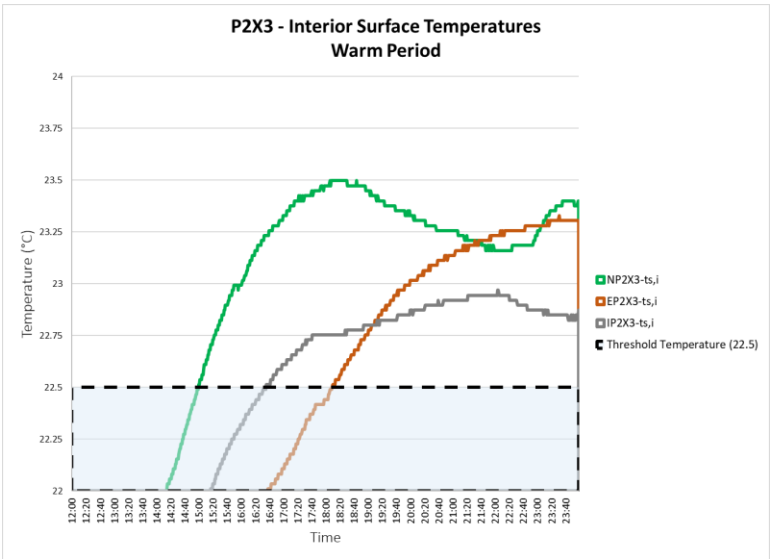


Figure (69) P2X3: Visualization assessment of CDM-warm period.

The smallest number of the above results represents the closest to the threshold of the assessment and means that the specimen performed better in terms of thermal comfort. The results of these assessments illustrate that the NP specimen shows the largest number of CDM in both periods. In the cold period, EP and IP were close to each other, but the EP performed slightly better for thermal comfort from the beginning of the period and was closer to the threshold. For the warm period, the IP specimen performed better for thermal comfort—with a distinguishable difference between IP and EP specimens. This difference was observed between the two PCM positions EP and IP, while again a more notable difference can be observed for the specimen without PCM (NP).

6.4.3 P2X3: Analysis of PCM Positioning Impact on Load Shifting Time

The effect of PCM positioning on load shifting time has been analyzed by graphical and arithmetic methods. The assessment of LST was accomplished by using the same strategy that was used for the previous configurations. Figure (70) and Figure (71) show the effects on load shifting from all specimens in the P2X3 configuration. In the cold period, the EP and IP specimens had a significant effect on load shifting time, although the IP specimen was more effective with almost 4 and a half hours of load shifting time. In the warm period, the EP and IP specimens performed well, but the EP specimen had a significantly longer load shifting time.

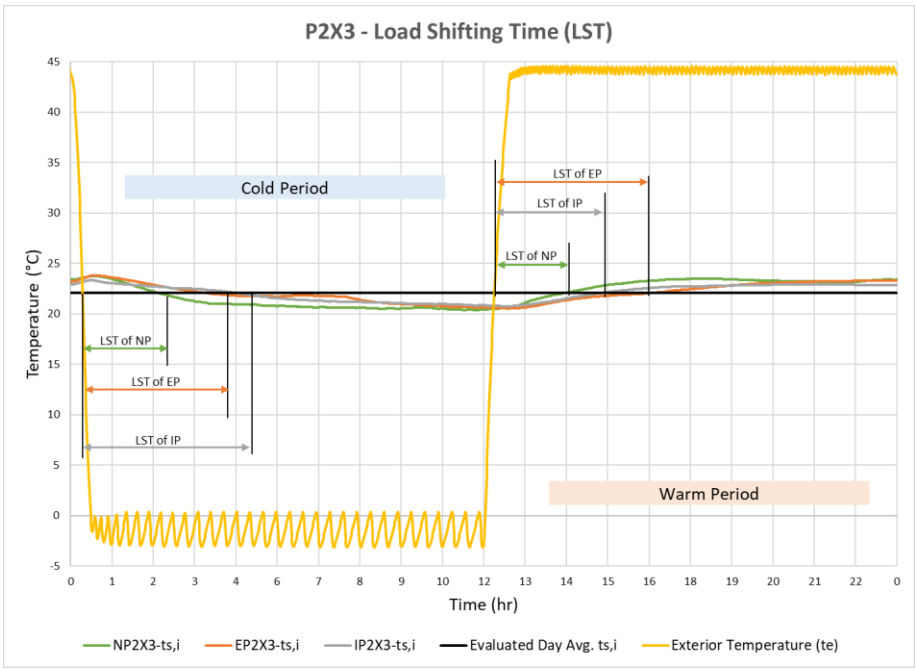


Figure (70) P2X3: Load shifting time with exterior temperature (t_e).

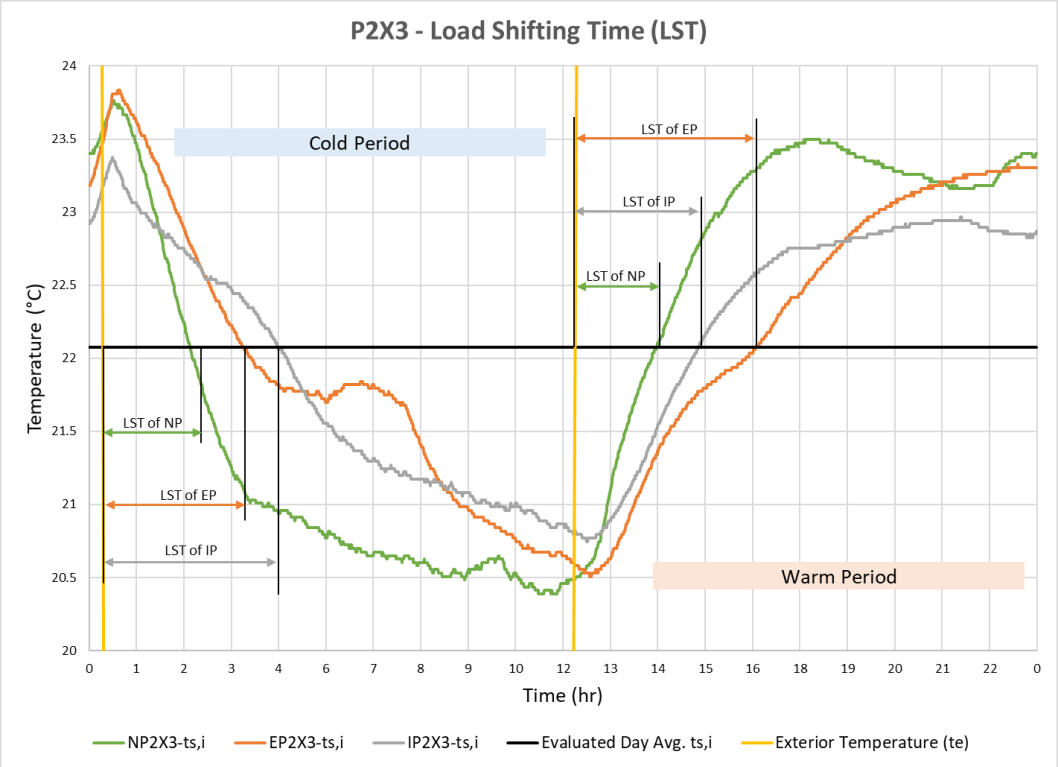


Figure (71) P2X3: Load shifting time (the range of interior surface temperature ($t_{s,i}$) for wall specimens).

The LTS metric has been used to calculate load shifting time for the P2X3 configuration and Figure (72) shows the results for a comparative analysis. The results demonstrate the effects of each specimen on load shifting time in cold and warm periods. In comparing these results, it can be observed that the IP specimen had more effect on load shifting by 4 hours and 27 minutes during the cooling process, but its effect during the heating process was less. On the other hand, the EP specimen had the reverse effect in both periods. In other words, it had less effect on shifting load time in the cold period with 3 hours and 37 minutes and a significant effect during the heating process with 4 hours and 34 minutes of load shifting time. During both periods, the specimen without PCM (NP) experienced only around 2 hours of load shifting time.

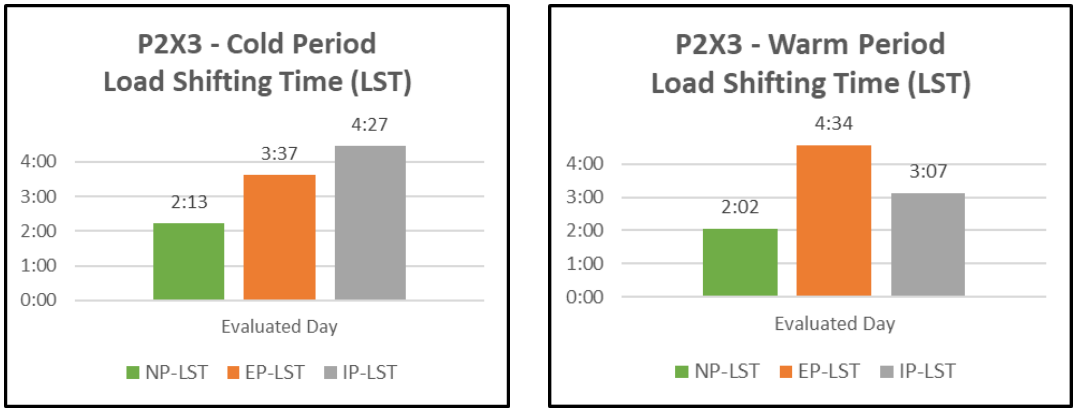


Figure (72) P2X3: Load shifting time in cold and warm periods.

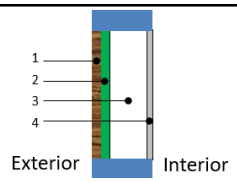
6.5 Experimental Limitations

This study has focused on the impact of utilizing PCM on thermal comfort and load shifting time. The specimens presented a common wood framed stud wall with cavities. Outdoor temperatures were controlled at fixed temperature differentials for precisely timed warm and cold periods. Phase change processes were limited to solid-liquid transformations as the utilized PCM was a bio-based mat with a melting point of 23 °C and the temperature differential never exceeded more than 25 °C. The thermal capacity of the PCM in solid and liquid states, as well as during of the transition period, was not considered during the experimental tests. The experiments focused on temperature changes and the effects on thermal performance of the PCM during heating and cooling processes in different positions within the building enclosure.

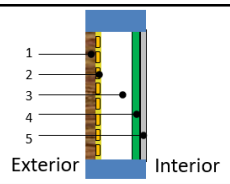
6.6 Conclusion of Experiments

The experiments have been conducted to study the PCM's behavior in different positions of a wall cavity within a building enclosure. Both numerical and graphical result of the PCM's responses across all experiments have been studied. The effects of PCM positioning on thermal comfort and load shifting were measured for precisely fixed but alternated cold and warm exterior climate cycles. The experiments indicate the effects of PCM positioning within the cavity of a building enclosure on thermal performance under the four different configurations as shown in Figure (73).

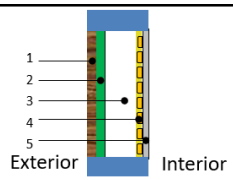
P1X1: 1 Layer of PCM & 1 Layer of XPS



NP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6.5 cm
4	Gypsum Board	1.3 cm

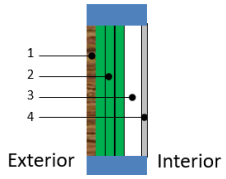


EP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of PCM	0.5 cm
3	Air Gap	6 cm
4	1-Layer of XPS	2.5 cm
5	Gypsum Board	1.3 cm

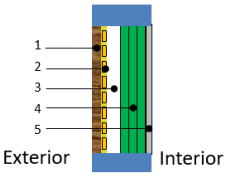


IP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6 cm
4	1-Layer of PCM	0.5 cm
5	Gypsum Board	1.3 cm

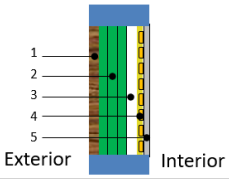
P1X3: 1 Layer of PCM & 3 Layers of XPS



NP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1.5 cm
4	Gypsum Board	1.3 cm

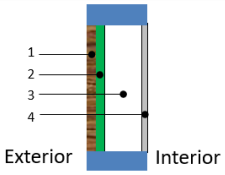


EP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of PCM	0.5 cm
3	Air Gap	1 cm
4	3-Layers of XPS	7.5 cm
5	Gypsum Board	1.3 cm

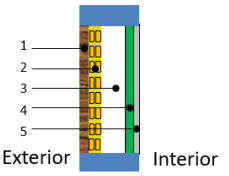


IP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1 cm
4	1-Layer of PCM	0.5 cm
5	Gypsum Board	1.3 cm

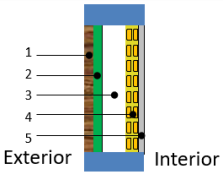
P2X1: 2 Layers of PCM & 1 Layer of XPS



NP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	6.5 cm
4	Gypsum Board	1.3cm

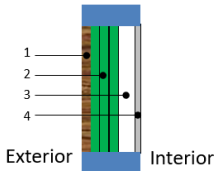


EP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	2-Layers of PCM	1 cm
3	Air Gap	5.5 cm
4	1-Layer of XPS	2.5 cm
5	Gypsum Board	1.3 cm

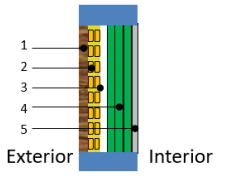


IP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	1-Layer of XPS	2.5 cm
3	Air Gap	5.5 cm
4	2-Layers of PCM	1 cm
5	Gypsum Board	1.3 cm

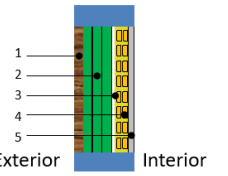
P2X3: 2 Layers of PCM & 3 Layers of XPS



NP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	1.5 cm
4	Gypsum Board	1.3 cm



EP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	2-Layers of PCM	1 cm
3	Air Gap	0.5 cm
4	3-Layers of XPS	7.5 cm
5	Gypsum Board	1.3 cm



IP		
Layer ID	Description	Thickness
1	OSB Sheathing	1.9 cm
2	3-Layers of XPS	7.5 cm
3	Air Gap	0.5 cm
4	2-Layers of PCM	1 cm
5	Gypsum Board	1.3 cm

Figure (73) Summary of specimens in all configurations.

This conclusion summarizes the EP and IP positioning and highlights their effects under different conditions. This summary uses the NP specimen as a baseline for comparison and calculates the differences for thermal comfort and load shifting time. It also uses a weighting factor method to demonstrate the importance of each position when utilized in a hot or cold climate for all configurations in terms of enhancing thermal comfort and increasing load shifting time. The larger number indicates a more significant contribution to thermal comfort. The outcomes of this method are shown in Table (14).

Table (14) Factor weights of EP and IP positions in all configurations.

Thermal Comfort								
	P1X1		**P1X3**		**P2X1**		**P2X3**	
	Cold period	Warm period	Cold period	Warm period	Cold period	Warm period	Cold period	Warm period
EP	521	316	289	440	660	838	419	207
IP	796	737	299	318	1049	1182	414	262
Load Shifting Time								
	P1X1		**P1X3**		**P2X1**		**P2X3**	
	Cold period	Warm period	Cold period	Warm period	Cold period	Warm period	Cold period	Warm period
EP	0:45	0:42	0:02	2:48	0:34	2:22	1:24	2:32
IP	2:22	0:51	1:25	0:20	3:27	1:32	2:14	1:05

In summary, the above table illustrates the following:

First: It is better to implement a wall assembly with PCMs in the exterior position of a cavity (**EP**) under the following conditions:

A. For Thermal Comfort:

The EP position performed better to enhance thermal comfort in hot climates with the P1X1 configuration (since it had a significant impact on enhancing thermal comfort). Also, it

performed better in cold climates with the P2X3 configuration, but with only a little advantage for thermal comfort.

B. For Load Shifting Time

The EP position performed better in hot climates with the P1X3, P2X1, and P2X3 configurations, although its impact in cold climates was less significant under all configurations. The most significant impact of the EP position was observed in hot climates with the P1X3 configuration.

Second: It is better to implement a wall assembly with PCMs in the interior position of a cavity (**IP**) under the following conditions:

A. For Thermal Comfort:

The IP position performed better in both climates with the P1X1 and P1X3 configurations (since it had a highly significant impact on enhancing thermal comfort). There was an improvement in thermal comfort in hot climates with P2X3, but it was only minor.

B. For Load Shifting Time

The IP position performed better in both climates for almost all configurations except for hot climates with P1X3, P2X1, and P2X3. The impact of the IP position on load shifting time was most evident in cold climates for P1X3 and P2X1.

7 CONCLUSION

7.1 MAJOR CONTRIBUTIONS

The purpose and focus of this research was to investigate effected differences when positioning a PCM within an enclosure assembly. The research primarily studied the variation of PCM positioning within building enclosures and their utilization toward thermal performance. As a way to objectively measure these effects, a metric for Comfort Degree Minutes (CDM) was developed to quantify the impact of PCM positioning on thermal performance and to indicate better positioning for PCMs in different temperatures—as well as a metric to measure load shifting time (LST) of PCMs in different positions. The research process showed the impact of PCMs for building applications, specifically in interior positions under most conditions.

The experiments tested the effect of PCM positioning, PCM quantity, and the thickness of insulation as parameters and measured their contributions to improving thermal performance in buildings. The purpose of conducting these experiments was to enhance the technical knowledge of PCM application in building construction and highlight the impact of a PCM's position on a building's thermal performance. The results of the laboratory experiments helped to quantify the differences between EP and IP in terms of positioning for thermal comfort and load shifting time.

This research illustrates effects of PCM positions on improving the thermal performance in buildings specifically in terms of thermal comfort and shifting loads to off peak times. Thus, the research will benefit the field of AEC as it objectively demonstrates the effect of each factor as a means for selecting the positioning of PCMs to achieve a desired thermal performance when utilized within building enclosures.

Finally, this research contributes by providing a broad understanding for promising technologies and an overall review of PCM selection criteria for building applications as well by studying the effects of PCM positioning in building enclosures and their utilization for thermal performance. The results of this study can therefore be used as an entry point to assist building owners, building designers, and building contractors in implementing PCMs in building construction and deciding the positioning of the PCM depending on climate conditions.

7.2 RESEARCH LIMITATIONS

This research is limited to thermal aspects in building enclosures, specifically of an external wall. Detailed assessments of HVAC loads, heat flux, overall energy consumptions, variations of design materials, or impact of relative humidity were not addressed. Rather, the experiments focused on temperature changes only and the effects on thermal performance of the PCM during heating and cooling processes in different positions within the building enclosure.

This research did not take into account broader impacts on overall energy consumption or measurements of median radiant temperatures (MRT) for an entire space, which could add further evidence to the comparison. The research did not go into the weight and cost of PCMs, which are very important factors and essential to be discussed to assess the viability of implementing them in building construction. Overall, the study demonstrates the advantages of PCMs in enhancement of energy savings and improving thermal comfort when they are installed in a wall cavity in most configurations, but further studies are needed to verify this observation with larger scale experiments and in conjunction with other material combinations.

7.3 FURTHER RESEARCH

Although the aim of this research was to study a variety of PCM positions within building enclosures and their utilization toward thermal performance, the focus of the research was mostly on the temperature profile of the interior surface of a 30 x 30 cm assembled specimen under different configurations, and not a detailed description and evaluation of a real-life application. Therefore, this research suggests testing PCMs in an existing building or a larger-sized chamber. The results of this research suggest that the duration of the tests would be best if conducted over a five-day basis to provide more data for comparison and study. In this way, the duration will be long enough to study the behavior of PCMs and their impact on thermal performance. According to the features of the PCM, the first cold and hot temperature periods are less practical for evaluation and they can be considered as a “swing-in” phase and a starting point, but it is better to exclude them from the evaluation. Moreover, conducting a comparison test of two types of PCMs with different thermal capacities and melting point could provide a broader understanding of the differences between PCMs for building applications. Studying the impact of PCMs on mean radiant temperature (MRT) is one useful way to further indicate the effect of PCMs on thermal comfort for a large-scale test. Also, studying heat flux during the experiment and overall energy

consumptions could provide a beneficial contribution to the assessment of a PCM's impact on energy savings in building applications.

Furthermore, since only one type of PCM with small size of specimens was investigated, there were other limitations to the current research. Thereby, conducting similar research in a large-scale test—including real data from a hot and cold climate region—is suggested in order to test the results of this research and to enhance the technical knowledge of utilizing PCMs in building construction. Finally, conducting more research on building materials that could improve thermal comfort for building occupants while reducing energy consumption would be beneficial for the AEC sector.

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9 APPENDICES

9.1 APPENDIX A – READING OF SENSORS CALIBRATION TEST FOR 1 DAY

1st Hour: Calibration Test					2nd Hour: Calibration Test					3rd Hour: Calibration Test				
Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4
0:00	22.11	22.08	22.06	22.01	1:00	22.15	22.11	22.13	22.03	2:00	22.15	22.08	22.11	22.01
0:01	22.13	22.08	22.08	22.03	1:01	22.15	22.11	22.13	22.06	2:01	22.13	22.06	22.11	21.99
0:02	22.15	22.11	22.11	22.03	1:02	22.18	22.11	22.15	22.08	2:02	22.13	22.06	22.11	21.99
0:03	22.13	22.08	22.11	22.01	1:03	22.15	22.08	22.13	22.03	2:03	22.13	22.08	22.11	22.01
0:04	22.13	22.11	22.11	22.03	1:04	22.15	22.08	22.13	22.03	2:04	22.13	22.08	22.11	22.03
0:05	22.18	22.11	22.13	22.06	1:05	22.13	22.08	22.11	22.01	2:05	22.13	22.08	22.13	22.06
0:06	22.18	22.13	22.13	22.06	1:06	22.13	22.08	22.11	22.01	2:06	22.15	22.11	22.13	22.06
0:07	22.18	22.13	22.15	22.08	1:07	22.13	22.08	22.11	22.01	2:07	22.15	22.11	22.13	22.06
0:08	22.18	22.13	22.15	22.08	1:08	22.13	22.08	22.11	22.01	2:08	22.15	22.11	22.13	22.06
0:09	22.18	22.13	22.15	22.08	1:09	22.13	22.08	22.11	22.01	2:09	22.15	22.11	22.13	22.06
0:10	22.18	22.13	22.15	22.08	1:10	22.13	22.08	22.13	22.03	2:10	22.15	22.11	22.13	22.03
0:11	22.20	22.15	22.15	22.08	1:11	22.15	22.11	22.13	22.03	2:11	22.15	22.11	22.13	22.06
0:12	22.20	22.15	22.18	22.08	1:12	22.15	22.11	22.13	22.03	2:12	22.15	22.11	22.13	22.06
0:13	22.20	22.15	22.18	22.11	1:13	22.15	22.11	22.13	22.03	2:13	22.13	22.11	22.13	22.06
0:14	22.20	22.15	22.18	22.08	1:14	22.15	22.11	22.13	22.03	2:14	22.15	22.08	22.13	22.03
0:15	22.20	22.15	22.18	22.08	1:15	22.15	22.08	22.13	22.03	2:15	22.13	22.06	22.11	22.03
0:16	22.20	22.15	22.18	22.08	1:16	22.15	22.08	22.11	22.03	2:16	22.11	22.06	22.11	21.99
0:17	22.20	22.15	22.18	22.11	1:17	22.15	22.08	22.13	22.03	2:17	22.11	22.06	22.08	21.99
0:18	22.23	22.15	22.18	22.13	1:18	22.15	22.08	22.13	22.03	2:18	22.13	22.08	22.11	22.01
0:19	22.23	22.15	22.18	22.11	1:19	22.15	22.11	22.13	22.03	2:19	22.13	22.08	22.11	21.99
0:20	22.23	22.15	22.18	22.11	1:20	22.15	22.11	22.13	22.03	2:20	22.13	22.08	22.11	21.99
0:21	22.20	22.15	22.18	22.11	1:21	22.15	22.11	22.13	22.03	2:21	22.13	22.08	22.08	22.01
0:22	22.23	22.18	22.20	22.13	1:22	22.15	22.11	22.13	22.03	2:22	22.13	22.08	22.11	22.01
0:23	22.23	22.18	22.20	22.13	1:23	22.15	22.11	22.13	22.03	2:23	22.13	22.08	22.11	22.01
0:24	22.23	22.18	22.20	22.13	1:24	22.15	22.08	22.13	22.03	2:24	22.11	22.06	22.11	22.01
0:25	22.23	22.18	22.20	22.13	1:25	22.15	22.11	22.13	22.03	2:25	22.13	22.08	22.11	22.01
0:26	22.23	22.15	22.20	22.13	1:26	22.15	22.11	22.13	22.03	2:26	22.13	22.08	22.11	22.01
0:27	22.23	22.18	22.20	22.13	1:27	22.15	22.11	22.13	22.03	2:27	22.13	22.08	22.11	22.01
0:28	22.23	22.15	22.20	22.13	1:28	22.15	22.11	22.13	22.03	2:28	22.13	22.06	22.11	22.01
0:29	22.20	22.15	22.18	22.11	1:29	22.15	22.11	22.13	22.06	2:29	22.13	22.06	22.11	22.01
0:30	22.20	22.13	22.18	22.11	1:30	22.15	22.11	22.13	22.03	2:30	22.13	22.06	22.11	22.03
0:31	22.20	22.15	22.18	22.08	1:31	22.15	22.11	22.13	22.01	2:31	22.13	22.08	22.11	22.06
0:32	22.18	22.13	22.15	22.06	1:32	22.13	22.11	22.13	22.01	2:32	22.15	22.08	22.11	22.06
0:33	22.18	22.13	22.15	22.06	1:33	22.15	22.11	22.13	22.06	2:33	22.15	22.08	22.11	22.06
0:34	22.18	22.13	22.15	22.06	1:34	22.15	22.11	22.13	22.03	2:34	22.15	22.11	22.13	22.06
0:35	22.18	22.13	22.15	22.08	1:35	22.13	22.11	22.13	22.01	2:35	22.15	22.11	22.13	22.06
0:36	22.18	22.13	22.15	22.06	1:36	22.15	22.11	22.13	22.03	2:36	22.18	22.11	22.13	22.06
0:37	22.18	22.13	22.15	22.06	1:37	22.13	22.08	22.13	22.01	2:37	22.18	22.11	22.13	22.06
0:38	22.18	22.13	22.15	22.06	1:38	22.13	22.08	22.11	22.01	2:38	22.18	22.11	22.15	22.08
0:39	22.15	22.11	22.13	22.03	1:39	22.13	22.11	22.11	22.01	2:39	22.18	22.13	22.15	22.06
0:40	22.15	22.11	22.13	22.03	1:40	22.13	22.11	22.11	22.01	2:40	22.15	22.11	22.13	22.06
0:41	22.15	22.11	22.13	22.03	1:41	22.15	22.11	22.13	22.03	2:41	22.15	22.11	22.13	22.03
0:42	22.15	22.11	22.13	22.03	1:42	22.15	22.11	22.13	22.06	2:42	22.13	22.06	22.11	22.03
0:43	22.15	22.11	22.13	22.06	1:43	22.15	22.08	22.13	22.06	2:43	22.11	22.03	22.11	21.99
0:44	22.15	22.11	22.13	22.03	1:44	22.15	22.08	22.13	22.06	2:44	22.11	22.03	22.08	21.99
0:45	22.15	22.11	22.13	22.03	1:45	22.15	22.11	22.13	22.06	2:45	22.11	22.06	22.08	21.99
0:46	22.15	22.11	22.13	22.03	1:46	22.18	22.11	22.13	22.08	2:46	22.13	22.06	22.11	22.01
0:47	22.15	22.11	22.13	22.03	1:47	22.15	22.08	22.13	22.06	2:47	22.13	22.06	22.11	22.01
0:48	22.15	22.11	22.13	22.06	1:48	22.15	22.08	22.13	22.06	2:48	22.13	22.06	22.11	22.01
0:49	22.15	22.11	22.13	22.06	1:49	22.15	22.11	22.13	22.06	2:49	22.11	22.03	22.11	22.01
0:50	22.15	22.11	22.13	22.06	1:50	22.15	22.11	22.13	22.06	2:50	22.13	22.06	22.11	22.01
0:51	22.18	22.11	22.13	22.06	1:51	22.15	22.08	22.13	22.06	2:51	22.13	22.06	22.11	22.03
0:52	22.15	22.08	22.13	22.03	1:52	22.15	22.11	22.13	22.06	2:52	22.13	22.06	22.11	22.03
0:53	22.15	22.11	22.13	22.03	1:53	22.15	22.11	22.13	22.06	2:53	22.15	22.08	22.11	22.03
0:54	22.15	22.08	22.13	22.01	1:54	22.18	22.11	22.13	22.08	2:54	22.15	22.08	22.11	22.03
0:55	22.15	22.11	22.13	22.06	1:55	22.18	22.11	22.13	22.08	2:55	22.15	22.08	22.11	22.03
0:56	22.18	22.11	22.15	22.06	1:56	22.18	22.11	22.15	22.08	2:56	22.15	22.08	22.11	22.03
0:57	22.15	22.11	22.13	22.06	1:57	22.18	22.11	22.13	22.08	2:57	22.15	22.06	22.11	22.01
0:58	22.18	22.11	22.13	22.06	1:58	22.18	22.11	22.13	22.06	2:58	22.15	22.08	22.11	22.03
0:59	22.15	22.11	22.13	22.03	1:59	22.15	22.08	22.11	22.03	2:59	22.15	22.08	22.11	22.06

4th Hour: Calibration Test					5th Hour: Calibration Test					6th Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
3:00	22.15	22.08	22.13	22.06	4:00	22.13	22.06	22.11	22.01	5:00	22.11	22.06	22.08	21.99
3:01	22.15	22.11	22.13	22.08	4:01	22.11	22.06	22.11	21.99	5:01	22.11	22.06	22.08	22.01
3:02	22.18	22.11	22.13	22.08	4:02	22.13	22.08	22.11	22.01	5:02	22.11	22.06	22.11	22.01
3:03	22.18	22.11	22.13	22.08	4:03	22.13	22.08	22.11	22.01	5:03	22.11	22.06	22.11	22.01
3:04	22.18	22.11	22.13	22.08	4:04	22.13	22.08	22.11	22.03	5:04	22.11	22.06	22.11	22.01
3:05	22.18	22.11	22.13	22.08	4:05	22.15	22.11	22.11	22.03	5:05	22.11	22.06	22.08	22.01
3:06	22.18	22.11	22.13	22.06	4:06	22.15	22.11	22.11	22.06	5:06	22.11	22.06	22.08	22.03
3:07	22.18	22.11	22.13	22.06	4:07	22.15	22.11	22.11	22.03	5:07	22.13	22.06	22.11	22.03
3:08	22.15	22.08	22.13	22.06	4:08	22.15	22.11	22.11	22.03	5:08	22.13	22.06	22.11	22.01
3:09	22.18	22.11	22.13	22.06	4:09	22.15	22.11	22.13	22.06	5:09	22.13	22.06	22.11	22.03
3:10	22.18	22.11	22.13	22.06	4:10	22.15	22.08	22.11	22.03	5:10	22.15	22.08	22.11	22.06
3:11	22.18	22.11	22.13	22.06	4:11	22.13	22.08	22.11	22.01	5:11	22.18	22.13	22.13	22.08
3:12	22.18	22.11	22.13	22.06	4:12	22.13	22.06	22.11	22.01	5:12	22.18	22.13	22.13	22.11
3:13	22.15	22.08	22.13	22.03	4:13	22.11	22.06	22.08	22.01	5:13	22.20	22.15	22.15	22.11
3:14	22.18	22.11	22.13	22.06	4:14	22.11	22.06	22.08	22.01	5:14	22.20	22.13	22.15	22.08
3:15	22.18	22.11	22.13	22.06	4:15	22.11	22.06	22.08	21.99	5:15	22.20	22.13	22.15	22.08
3:16	22.18	22.11	22.13	22.06	4:16	22.11	22.06	22.08	22.01	5:16	22.18	22.13	22.15	22.08
3:17	22.18	22.11	22.13	22.06	4:17	22.11	22.06	22.08	22.01	5:17	22.18	22.13	22.15	22.06
3:18	22.15	22.11	22.13	22.06	4:18	22.11	22.06	22.08	22.01	5:18	22.18	22.11	22.13	22.08
3:19	22.15	22.11	22.13	22.06	4:19	22.11	22.06	22.08	21.99	5:19	22.15	22.11	22.13	22.06
3:20	22.18	22.11	22.13	22.06	4:20	22.11	22.06	22.08	21.99	5:20	22.15	22.11	22.13	22.06
3:21	22.18	22.11	22.13	22.06	4:21	22.11	22.06	22.08	21.99	5:21	22.18	22.11	22.13	22.06
3:22	22.15	22.11	22.13	22.03	4:22	22.11	22.03	22.06	21.99	5:22	22.18	22.11	22.13	22.06
3:23	22.15	22.11	22.13	22.03	4:23	22.11	22.03	22.06	21.99	5:23	22.15	22.08	22.13	22.06
3:24	22.15	22.11	22.13	22.03	4:24	22.11	22.06	22.08	22.01	5:24	22.15	22.11	22.13	22.06
3:25	22.15	22.11	22.13	22.03	4:25	22.11	22.06	22.08	22.01	5:25	22.18	22.11	22.13	22.08
3:26	22.15	22.11	22.13	22.03	4:26	22.11	22.06	22.08	22.01	5:26	22.18	22.13	22.15	22.08
3:27	22.13	22.08	22.13	22.01	4:27	22.11	22.06	22.08	22.01	5:27	22.18	22.11	22.15	22.08
3:28	22.13	22.08	22.11	22.01	4:28	22.11	22.06	22.11	22.01	5:28	22.18	22.11	22.13	22.08
3:29	22.13	22.08	22.11	22.01	4:29	22.11	22.08	22.11	22.01	5:29	22.15	22.08	22.13	22.06
3:30	22.13	22.08	22.13	22.01	4:30	22.13	22.08	22.11	22.03	5:30	22.15	22.11	22.13	22.03
3:31	22.15	22.11	22.13	22.03	4:31	22.13	22.11	22.11	22.03	5:31	22.15	22.08	22.13	22.06
3:32	22.13	22.08	22.13	22.01	4:32	22.13	22.08	22.11	22.03	5:32	22.15	22.11	22.13	22.06
3:33	22.13	22.08	22.13	22.03	4:33	22.15	22.11	22.11	22.06	5:33	22.15	22.11	22.13	22.06
3:34	22.15	22.11	22.13	22.06	4:34	22.15	22.08	22.11	22.06	5:34	22.18	22.11	22.13	22.08
3:35	22.18	22.11	22.15	22.06	4:35	22.13	22.08	22.11	22.03	5:35	22.18	22.11	22.13	22.06
3:36	22.15	22.11	22.13	22.03	4:36	22.13	22.08	22.11	22.03	5:36	22.15	22.11	22.13	22.06
3:37	22.13	22.08	22.13	22.03	4:37	22.13	22.06	22.11	22.03	5:37	22.15	22.08	22.13	22.06
3:38	22.13	22.06	22.13	22.03	4:38	22.13	22.06	22.11	22.01	5:38	22.15	22.08	22.13	22.03
3:39	22.11	22.06	22.11	21.99	4:39	22.11	22.03	22.11	22.01	5:39	22.15	22.08	22.13	22.03
3:40	22.11	22.06	22.11	21.99	4:40	22.11	22.03	22.08	22.01	5:40	22.15	22.08	22.13	22.03
3:41	22.11	22.06	22.11	21.99	4:41	22.11	22.06	22.11	22.01	5:41	22.15	22.08	22.13	22.03
3:42	22.08	22.03	22.08	21.96	4:42	22.13	22.06	22.11	22.03	5:42	22.15	22.08	22.13	22.06
3:43	22.08	22.03	22.08	21.96	4:43	22.13	22.03	22.11	22.03	5:43	22.15	22.08	22.13	22.03
3:44	22.08	22.01	22.08	21.94	4:44	22.11	22.03	22.11	22.01	5:44	22.15	22.08	22.13	22.03
3:45	22.06	22.01	22.08	21.96	4:45	22.11	22.03	22.08	22.01	5:45	22.15	22.11	22.13	22.06
3:46	22.06	22.01	22.06	21.94	4:46	22.11	22.06	22.11	22.01	5:46	22.15	22.08	22.13	22.03
3:47	22.08	22.01	22.06	21.94	4:47	22.11	22.06	22.11	22.01	5:47	22.13	22.08	22.13	22.03
3:48	22.06	22.01	22.06	21.94	4:48	22.11	22.06	22.11	22.01	5:48	22.15	22.08	22.13	22.03
3:49	22.08	22.03	22.06	21.94	4:49	22.13	22.06	22.11	22.03	5:49	22.15	22.08	22.13	22.03
3:50	22.08	22.03	22.06	21.96	4:50	22.13	22.06	22.11	22.03	5:50	22.13	22.06	22.11	22.01
3:51	22.08	22.03	22.06	21.96	4:51	22.11	22.06	22.11	22.01	5:51	22.13	22.06	22.11	22.01
3:52	22.08	22.03	22.06	21.96	4:52	22.11	22.06	22.11	22.01	5:52	22.13	22.08	22.11	22.01
3:53	22.08	22.03	22.06	21.96	4:53	22.11	22.06	22.11	22.01	5:53	22.13	22.08	22.11	22.01
3:54	22.08	22.03	22.06	21.96	4:54	22.11	22.03	22.11	21.99	5:54	22.13	22.08	22.13	22.03
3:55	22.11	22.06	22.08	21.99	4:55	22.11	22.06	22.08	21.99	5:55	22.13	22.08	22.13	22.03
3:56	22.11	22.06	22.08	22.01	4:56	22.11	22.06	22.08	21.99	5:56	22.13	22.08	22.13	22.06
3:57	22.11	22.06	22.08	21.99	4:57	22.08	22.03	22.08	21.96	5:57	22.15	22.11	22.13	22.06
3:58	22.11	22.06	22.08	22.01	4:58	22.11	22.06	22.08	21.96	5:58	22.15	22.08	22.13	22.06
3:59	22.13	22.08	22.11	22.03	4:59	22.11	22.06	22.08	21.99	5:59	22.15	22.08	22.13	22.06

7th Hour: Calibration Test					8th Hour: Calibration Test					9th Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
6:00	22.13	22.06	22.11	22.03	7:00	22.15	22.11	22.13	22.06	8:00	22.13	22.06	22.11	22.03
6:01	22.13	22.06	22.11	22.03	7:01	22.15	22.11	22.13	22.06	8:01	22.13	22.06	22.11	22.03
6:02	22.13	22.06	22.11	22.03	7:02	22.15	22.08	22.13	22.03	8:02	22.13	22.03	22.11	22.01
6:03	22.13	22.08	22.11	22.03	7:03	22.13	22.08	22.11	22.03	8:03	22.13	22.03	22.11	22.01
6:04	22.13	22.08	22.11	22.06	7:04	22.13	22.06	22.11	22.03	8:04	22.13	22.06	22.11	22.01
6:05	22.15	22.08	22.11	22.06	7:05	22.13	22.08	22.11	22.03	8:05	22.08	22.03	22.08	21.94
6:06	22.15	22.08	22.11	22.06	7:06	22.15	22.08	22.13	22.03	8:06	22.01	21.89	22.01	21.82
6:07	22.15	22.08	22.13	22.06	7:07	22.15	22.08	22.13	22.03	8:07	21.92	21.80	21.92	21.75
6:08	22.15	22.08	22.11	22.03	7:08	22.15	22.11	22.13	22.06	8:08	21.82	21.70	21.84	21.63
6:09	22.15	22.08	22.11	22.03	7:09	22.18	22.08	22.13	22.06	8:09	21.77	21.63	21.80	21.56
6:10	22.13	22.08	22.11	22.01	7:10	22.15	22.06	22.13	22.03	8:10	21.65	21.56	21.72	21.46
6:11	22.15	22.08	22.11	22.03	7:11	22.13	22.06	22.11	22.03	8:11	21.63	21.51	21.68	21.44
6:12	22.15	22.11	22.13	22.03	7:12	22.15	22.08	22.13	22.06	8:12	21.60	21.51	21.65	21.39
6:13	22.15	22.11	22.13	22.03	7:13	22.15	22.08	22.13	22.03	8:13	21.58	21.53	21.65	21.39
6:14	22.15	22.11	22.13	22.03	7:14	22.15	22.08	22.13	22.03	8:14	21.60	21.53	21.65	21.39
6:15	22.13	22.08	22.11	22.01	7:15	22.13	22.08	22.11	22.03	8:15	21.60	21.53	21.65	21.41
6:16	22.13	22.08	22.11	22.01	7:16	22.15	22.08	22.11	22.06	8:16	21.63	21.56	21.65	21.44
6:17	22.13	22.08	22.11	22.03	7:17	22.15	22.11	22.13	22.06	8:17	21.65	21.58	21.68	21.49
6:18	22.15	22.11	22.13	22.06	7:18	22.18	22.11	22.13	22.08	8:18	21.70	21.63	21.70	21.53
6:19	22.13	22.08	22.13	22.03	7:19	22.18	22.11	22.13	22.08	8:19	21.72	21.60	21.72	21.53
6:20	22.13	22.08	22.11	22.03	7:20	22.18	22.11	22.13	22.08	8:20	21.72	21.63	21.72	21.53
6:21	22.13	22.08	22.13	22.01	7:21	22.18	22.11	22.13	22.08	8:21	21.72	21.60	21.72	21.51
6:22	22.13	22.08	22.13	22.03	7:22	22.18	22.11	22.13	22.08	8:22	21.70	21.60	21.70	21.51
6:23	22.13	22.08	22.13	22.03	7:23	22.15	22.11	22.13	22.06	8:23	21.68	21.58	21.70	21.46
6:24	22.15	22.11	22.13	22.06	7:24	22.15	22.11	22.13	22.08	8:24	21.68	21.58	21.70	21.49
6:25	22.15	22.08	22.13	22.03	7:25	22.18	22.11	22.13	22.08	8:25	21.65	21.56	21.68	21.49
6:26	22.15	22.11	22.13	22.06	7:26	22.18	22.11	22.13	22.08	8:26	21.68	21.60	21.70	21.51
6:27	22.15	22.08	22.13	22.06	7:27	22.15	22.08	22.13	22.06	8:27	21.68	21.65	21.70	21.51
6:28	22.15	22.08	22.13	22.06	7:28	22.15	22.08	22.13	22.03	8:28	21.68	21.63	21.70	21.51
6:29	22.15	22.08	22.13	22.06	7:29	22.15	22.08	22.13	22.06	8:29	21.68	21.60	21.70	21.49
6:30	22.15	22.08	22.13	22.03	7:30	22.15	22.08	22.13	22.06	8:30	21.68	21.60	21.70	21.51
6:31	22.15	22.08	22.11	22.03	7:31	22.15	22.08	22.13	22.06	8:31	21.68	21.60	21.70	21.51
6:32	22.15	22.08	22.11	22.03	7:32	22.15	22.08	22.13	22.03	8:32	21.70	21.63	21.72	21.53
6:33	22.13	22.06	22.11	22.03	7:33	22.13	22.08	22.11	22.03	8:33	21.70	21.65	21.72	21.53
6:34	22.15	22.08	22.13	22.03	7:34	22.13	22.08	22.11	22.03	8:34	21.72	21.68	21.75	21.56
6:35	22.15	22.11	22.13	22.06	7:35	22.15	22.08	22.11	22.06	8:35	21.72	21.70	21.75	21.58
6:36	22.15	22.08	22.13	22.06	7:36	22.15	22.08	22.13	22.06	8:36	21.77	21.68	21.75	21.58
6:37	22.15	22.08	22.13	22.03	7:37	22.15	22.11	22.13	22.06	8:37	21.77	21.70	21.75	21.60
6:38	22.13	22.06	22.11	22.03	7:38	22.15	22.08	22.13	22.06	8:38	21.77	21.72	21.77	21.60
6:39	22.13	22.08	22.11	22.03	7:39	22.15	22.08	22.13	22.03	8:39	21.77	21.72	21.77	21.58
6:40	22.13	22.06	22.11	22.03	7:40	22.15	22.08	22.13	22.06	8:40	21.75	21.70	21.75	21.56
6:41	22.13	22.08	22.11	22.01	7:41	22.15	22.08	22.13	22.06	8:41	21.72	21.65	21.72	21.53
6:42	22.13	22.08	22.11	22.01	7:42	22.15	22.08	22.13	22.06	8:42	21.75	21.70	21.75	21.60
6:43	22.15	22.08	22.11	22.03	7:43	22.15	22.08	22.13	22.06	8:43	21.80	21.70	21.77	21.63
6:44	22.15	22.08	22.11	22.03	7:44	22.15	22.08	22.13	22.06	8:44	21.80	21.75	21.80	21.65
6:45	22.15	22.08	22.13	22.06	7:45	22.15	22.08	22.13	22.06	8:45	21.84	21.80	21.82	21.72
6:46	22.15	22.08	22.13	22.06	7:46	22.13	22.06	22.11	22.03	8:46	21.87	21.82	21.84	21.75
6:47	22.15	22.08	22.13	22.06	7:47	22.13	22.06	22.11	22.03	8:47	21.92	21.84	21.87	21.80
6:48	22.15	22.08	22.13	22.06	7:48	22.13	22.08	22.11	22.03	8:48	21.94	21.87	21.89	21.82
6:49	22.15	22.08	22.13	22.06	7:49	22.15	22.08	22.13	22.06	8:49	21.94	21.89	21.92	21.82
6:50	22.15	22.11	22.13	22.08	7:50	22.15	22.08	22.13	22.06	8:50	21.96	21.89	21.92	21.84
6:51	22.18	22.11	22.13	22.08	7:51	22.15	22.08	22.13	22.06	8:51	21.99	21.92	21.94	21.87
6:52	22.18	22.11	22.13	22.08	7:52	22.15	22.08	22.11	22.06	8:52	21.99	21.92	21.94	21.89
6:53	22.18	22.11	22.15	22.11	7:53	22.15	22.08	22.13	22.06	8:53	21.99	21.94	21.96	21.89
6:54	22.18	22.11	22.13	22.11	7:54	22.13	22.06	22.11	22.03	8:54	21.99	21.92	21.96	21.87
6:55	22.18	22.11	22.13	22.11	7:55	22.13	22.06	22.11	22.03	8:55	21.96	21.87	21.94	21.84
6:56	22.18	22.11	22.13	22.08	7:56	22.13	22.06	22.11	22.03	8:56	21.94	21.84	21.92	21.82
6:57	22.18	22.11	22.13	22.08	7:57	22.13	22.06	22.11	22.06	8:57	21.92	21.84	21.92	21.77
6:58	22.15	22.11	22.13	22.06	7:58	22.15	22.08	22.11	22.06	8:58	21.92	21.84	21.89	21.77
6:59	22.15	22.11	22.13	22.06	7:59	22.15	22.08	22.11	22.06	8:59	21.92	21.84	21.92	21.77

10th Hour: Calibration Test					11th Hour: Calibration Test					12th Hour: Calibration Test				
Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4
9:00	21.92	21.84	21.92	21.77	10:00	22.11	22.01	22.06	22.03	11:00	22.13	22.03	22.08	22.03
9:01	21.92	21.87	21.92	21.77	10:01	22.11	22.01	22.06	22.01	11:01	22.13	22.03	22.08	22.06
9:02	21.92	21.87	21.92	21.77	10:02	22.08	22.01	22.06	22.01	11:02	22.13	22.06	22.08	22.06
9:03	21.92	21.87	21.92	21.80	10:03	22.11	22.01	22.06	22.01	11:03	22.13	22.03	22.08	22.06
9:04	21.94	21.87	21.92	21.82	10:04	22.08	22.01	22.06	22.01	11:04	22.13	22.06	22.08	22.06
9:05	21.96	21.89	21.94	21.84	10:05	22.08	22.01	22.06	22.01	11:05	22.13	22.06	22.08	22.06
9:06	21.96	21.92	21.94	21.84	10:06	22.08	22.01	22.06	22.01	11:06	22.13	22.03	22.08	22.06
9:07	21.99	21.92	21.94	21.84	10:07	22.11	22.01	22.06	22.01	11:07	22.13	22.03	22.08	22.06
9:08	21.99	21.92	21.96	21.87	10:08	22.11	22.01	22.06	22.03	11:08	22.13	22.03	22.08	22.03
9:09	21.99	21.92	21.96	21.87	10:09	22.11	22.01	22.06	22.03	11:09	22.08	21.99	22.06	21.99
9:10	21.99	21.92	21.96	21.87	10:10	22.11	22.01	22.06	22.03	11:10	22.08	21.99	22.03	21.96
9:11	22.01	21.94	21.96	21.92	10:11	22.08	22.01	22.06	22.01	11:11	22.06	21.99	22.03	21.96
9:12	22.01	21.94	21.99	21.89	10:12	22.11	22.01	22.06	22.01	11:12	22.08	21.99	22.03	21.99
9:13	22.03	21.96	21.99	21.92	10:13	22.11	22.03	22.06	22.01	11:13	22.08	21.99	22.03	21.96
9:14	22.03	21.96	21.99	21.92	10:14	22.08	22.01	22.06	22.01	11:14	22.08	21.99	22.03	21.99
9:15	22.06	21.99	22.01	21.94	10:15	22.08	21.99	22.06	21.99	11:15	22.08	21.99	22.06	22.01
9:16	22.06	21.99	22.01	21.92	10:16	22.08	21.99	22.06	22.01	11:16	22.08	22.01	22.06	22.01
9:17	22.03	21.99	22.01	21.92	10:17	22.08	21.99	22.06	22.01	11:17	22.11	22.01	22.06	22.01
9:18	22.06	21.99	22.03	21.94	10:18	22.11	22.01	22.06	22.01	11:18	22.11	22.01	22.06	22.01
9:19	22.06	21.99	22.03	21.94	10:19	22.11	22.01	22.06	22.03	11:19	22.11	22.01	22.06	22.03
9:20	22.06	21.99	22.03	21.92	10:20	22.11	22.01	22.08	22.03	11:20	22.11	22.03	22.06	22.01
9:21	22.06	22.01	22.03	21.94	10:21	22.11	22.01	22.08	22.03	11:21	22.11	22.03	22.08	22.03
9:22	22.08	22.01	22.03	21.96	10:22	22.11	22.01	22.06	22.03	11:22	22.11	22.03	22.08	22.03
9:23	22.08	22.01	22.03	21.94	10:23	22.11	22.03	22.08	22.03	11:23	22.13	22.03	22.08	22.06
9:24	22.08	22.01	22.03	21.96	10:24	22.11	22.03	22.08	22.06	11:24	22.13	22.03	22.08	22.06
9:25	22.08	22.03	22.06	21.99	10:25	22.13	22.03	22.08	22.03	11:25	22.13	22.03	22.08	22.06
9:26	22.11	22.03	22.06	21.99	10:26	22.13	22.03	22.08	22.03	11:26	22.13	22.03	22.11	22.06
9:27	22.11	22.03	22.06	21.99	10:27	22.13	22.03	22.08	22.03	11:27	22.13	22.06	22.11	22.06
9:28	22.08	22.03	22.06	21.99	10:28	22.13	22.03	22.08	22.03	11:28	22.13	22.03	22.11	22.06
9:29	22.11	22.03	22.06	21.96	10:29	22.13	22.03	22.08	22.03	11:29	22.13	22.03	22.11	22.06
9:30	22.11	22.03	22.06	21.96	10:30	22.13	22.03	22.08	22.06	11:30	22.13	22.06	22.11	22.06
9:31	22.11	22.03	22.06	21.96	10:31	22.13	22.03	22.08	22.03	11:31	22.13	22.06	22.11	22.03
9:32	22.11	22.03	22.06	21.99	10:32	22.11	22.01	22.08	22.03	11:32	22.08	21.99	22.06	21.94
9:33	22.11	22.06	22.08	22.01	10:33	22.13	22.03	22.08	22.03	11:33	22.01	21.94	22.01	21.89
9:34	22.13	22.06	22.08	22.01	10:34	22.13	22.03	22.08	22.03	11:34	22.01	21.96	22.01	21.89
9:35	22.11	22.06	22.08	22.01	10:35	22.13	22.03	22.08	22.03	11:35	22.03	21.96	22.01	21.92
9:36	22.11	22.06	22.08	22.01	10:36	22.13	22.03	22.08	22.03	11:36	22.06	22.01	22.03	21.96
9:37	22.13	22.03	22.08	22.01	10:37	22.13	22.03	22.08	22.03	11:37	22.08	22.01	22.06	21.99
9:38	22.13	22.03	22.08	22.01	10:38	22.13	22.03	22.08	22.03	11:38	22.11	22.03	22.08	22.03
9:39	22.13	22.03	22.08	22.01	10:39	22.13	22.03	22.08	22.03	11:39	22.11	22.03	22.08	22.01
9:40	22.11	22.03	22.08	22.03	10:40	22.13	22.03	22.08	22.03	11:40	22.06	21.94	22.03	21.94
9:41	22.11	22.01	22.06	21.99	10:41	22.13	22.03	22.08	22.03	11:41	22.03	21.92	22.01	21.92
9:42	22.11	22.03	22.08	22.01	10:42	22.13	22.03	22.08	22.06	11:42	22.03	21.92	21.99	21.92
9:43	22.11	22.03	22.08	22.01	10:43	22.13	22.03	22.08	22.03	11:43	22.03	21.94	21.99	21.92
9:44	22.08	22.01	22.06	21.99	10:44	22.13	22.03	22.08	22.03	11:44	22.03	21.94	22.01	21.94
9:45	22.08	22.01	22.06	21.99	10:45	22.13	22.03	22.08	22.03	11:45	22.06	21.96	22.01	21.96
9:46	22.08	22.01	22.06	21.99	10:46	22.13	22.03	22.08	22.03	11:46	22.06	21.96	22.01	21.96
9:47	22.08	22.01	22.06	22.01	10:47	22.13	22.03	22.08	22.06	11:47	22.08	21.99	22.03	21.99
9:48	22.08	22.01	22.06	21.99	10:48	22.13	22.03	22.08	22.03	11:48	22.08	22.01	22.03	22.01
9:49	22.11	22.01	22.06	21.99	10:49	22.11	22.03	22.08	22.03	11:49	22.08	22.01	22.06	22.01
9:50	22.11	22.01	22.06	22.01	10:50	22.13	22.03	22.08	22.03	11:50	22.11	22.03	22.06	22.01
9:51	22.11	22.01	22.06	22.01	10:51	22.13	22.06	22.08	22.06	11:51	22.11	22.03	22.06	22.03
9:52	22.08	22.01	22.06	22.01	10:52	22.13	22.03	22.08	22.06	11:52	22.11	22.03	22.08	22.03
9:53	22.08	22.01	22.06	21.99	10:53	22.13	22.03	22.08	22.03	11:53	22.11	22.03	22.08	22.03
9:54	22.08	22.01	22.06	21.99	10:54	22.13	22.03	22.08	22.03	11:54	22.13	22.06	22.08	22.06
9:55	22.08	22.01	22.06	22.01	10:55	22.13	22.03	22.08	22.03	11:55	22.13	22.06	22.08	22.06
9:56	22.08	22.01	22.06	22.01	10:56	22.11	22.03	22.08	22.03	11:56	22.11	22.01	22.06	22.01
9:57	22.08	22.01	22.06	22.01	10:57	22.11	22.03	22.08	22.03	11:57	22.08	21.99	22.06	21.99
9:58	22.11	22.01	22.06	22.01	10:58	22.11	22.03	22.08	22.03	11:58	22.08	21.99	22.06	21.99
9:59	22.11	22.01	22.06	22.03	10:59	22.11	22.03	22.08	22.03	11:59	22.08	21.99	22.06	22.01

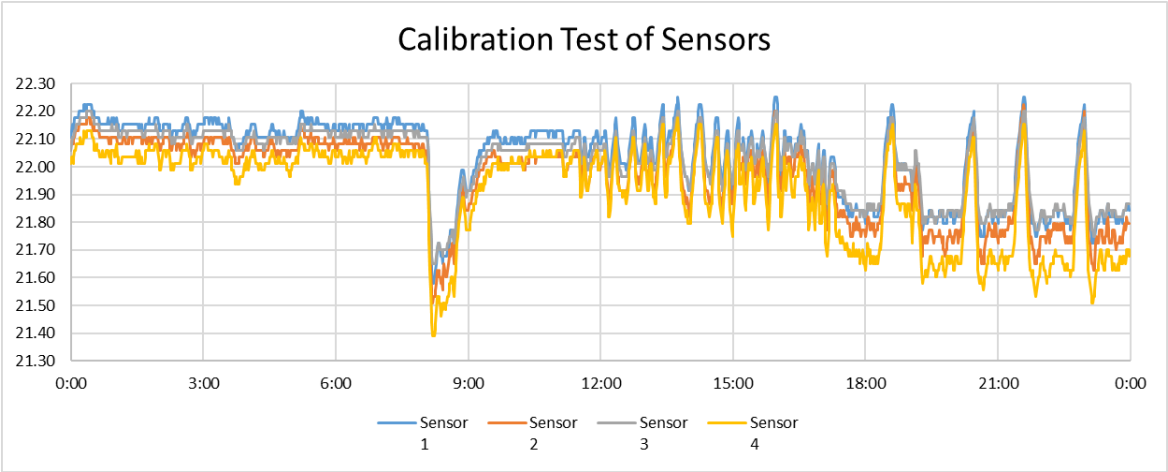
13th Hour: Calibration Test					14th Hour: Calibration Test					15th Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
12:00	22.08	22.01	22.06	22.01	13:00	22.15	22.08	22.11	22.08	14:00	21.92	21.84	21.94	21.80
12:01	22.08	22.01	22.06	22.01	13:01	22.13	22.03	22.08	22.03	14:01	21.92	21.82	21.92	21.80
12:02	22.11	22.01	22.06	22.01	13:02	22.11	21.99	22.06	22.01	14:02	21.92	21.84	21.92	21.80
12:03	22.11	22.03	22.06	22.03	13:03	22.08	21.99	22.03	21.96	14:03	21.94	21.87	21.92	21.82
12:04	22.11	22.03	22.08	22.03	13:04	22.06	21.96	22.01	21.92	14:04	21.96	21.92	21.94	21.89
12:05	22.11	22.03	22.08	22.03	13:05	22.06	21.96	22.01	21.92	14:05	22.01	21.94	21.99	21.92
12:06	22.13	22.03	22.08	22.06	13:06	22.06	21.99	22.03	21.96	14:06	22.03	21.96	22.01	21.96
12:07	22.13	22.03	22.08	22.03	13:07	22.08	22.01	22.03	21.99	14:07	22.06	21.99	22.03	21.99
12:08	22.08	21.96	22.03	21.94	13:08	22.11	22.03	22.06	22.01	14:08	22.08	22.03	22.06	22.01
12:09	22.03	21.94	22.01	21.92	13:09	22.11	22.01	22.06	22.01	14:09	22.11	22.03	22.08	22.03
12:10	22.01	21.92	21.99	21.87	13:10	22.06	21.94	22.03	21.94	14:10	22.15	22.08	22.11	22.06
12:11	21.96	21.87	21.96	21.82	13:11	22.03	21.94	22.01	21.92	14:11	22.15	22.11	22.13	22.08
12:12	21.96	21.87	21.96	21.82	13:12	22.01	21.92	21.99	21.89	14:12	22.18	22.13	22.15	22.11
12:13	21.96	21.89	21.96	21.84	13:13	22.01	21.92	21.99	21.89	14:13	22.20	22.15	22.15	22.13
12:14	21.99	21.92	21.96	21.89	13:14	22.01	21.92	21.99	21.87	14:14	22.23	22.15	22.18	22.15
12:15	22.01	21.94	21.99	21.92	13:15	22.01	21.92	21.99	21.87	14:15	22.23	22.18	22.18	22.15
12:16	22.06	21.99	22.01	21.96	13:16	22.01	21.96	21.99	21.92	14:16	22.23	22.18	22.18	22.15
12:17	22.08	22.01	22.03	22.01	13:17	22.03	21.99	22.01	21.94	14:17	22.23	22.18	22.18	22.15
12:18	22.11	22.03	22.06	22.03	13:18	22.08	22.01	22.03	21.99	14:18	22.20	22.13	22.15	22.11
12:19	22.13	22.06	22.08	22.06	13:19	22.11	22.06	22.08	22.03	14:19	22.15	22.06	22.13	22.03
12:20	22.15	22.08	22.11	22.08	13:20	22.13	22.08	22.11	22.06	14:20	22.11	22.01	22.08	21.96
12:21	22.18	22.11	22.13	22.11	13:21	22.15	22.11	22.13	22.08	14:21	22.06	21.96	22.06	21.94
12:22	22.13	22.03	22.08	22.01	13:22	22.18	22.13	22.15	22.11	14:22	22.03	21.94	22.01	21.89
12:23	22.08	21.96	22.03	21.94	13:23	22.20	22.15	22.15	22.13	14:23	22.01	21.92	22.01	21.87
12:24	22.06	21.96	22.01	21.94	13:24	22.23	22.18	22.18	22.15	14:24	21.99	21.92	21.99	21.87
12:25	22.06	21.94	22.01	21.94	13:25	22.23	22.18	22.18	22.15	14:25	21.99	21.92	21.99	21.87
12:26	22.03	21.92	21.99	21.92	13:26	22.20	22.08	22.15	22.06	14:26	21.96	21.89	21.96	21.84
12:27	22.01	21.92	21.99	21.92	13:27	22.11	22.01	22.08	21.94	14:27	21.96	21.89	21.96	21.84
12:28	22.01	21.92	21.96	21.92	13:28	22.03	21.96	22.03	21.89	14:28	21.96	21.87	21.96	21.82
12:29	22.01	21.92	21.96	21.92	13:29	22.03	21.96	22.03	21.89	14:29	21.96	21.89	21.94	21.84
12:30	22.01	21.92	21.96	21.89	13:30	22.06	21.99	22.03	21.92	14:30	21.99	21.89	21.96	21.87
12:31	22.01	21.92	21.96	21.92	13:31	22.08	22.01	22.06	21.96	14:31	22.01	21.92	21.96	21.87
12:32	22.01	21.92	21.96	21.92	13:32	22.11	22.03	22.08	22.01	14:32	22.03	21.96	21.99	21.92
12:33	22.01	21.92	21.96	21.92	13:33	22.13	22.03	22.08	22.03	14:33	22.06	22.01	22.01	21.96
12:34	22.01	21.92	21.96	21.89	13:34	22.11	22.03	22.08	22.01	14:34	22.08	22.03	22.06	21.99
12:35	21.99	21.89	21.96	21.87	13:35	22.11	22.03	22.08	22.01	14:35	22.13	22.06	22.08	22.03
12:36	21.99	21.92	21.96	21.89	13:36	22.13	22.06	22.08	22.03	14:36	22.15	22.11	22.11	22.06
12:37	22.01	21.94	21.99	21.92	13:37	22.13	22.06	22.11	22.03	14:37	22.18	22.11	22.13	22.08
12:38	22.03	21.96	22.01	21.96	13:38	22.13	22.08	22.11	22.06	14:38	22.18	22.11	22.13	22.11
12:39	22.06	21.99	22.03	21.99	13:39	22.15	22.11	22.13	22.08	14:39	22.18	22.11	22.13	22.11
12:40	22.08	22.01	22.06	22.01	13:40	22.18	22.11	22.13	22.11	14:40	22.13	22.03	22.11	22.01
12:41	22.11	22.03	22.06	22.03	13:41	22.18	22.13	22.15	22.13	14:41	22.06	21.94	22.03	21.92
12:42	22.13	22.06	22.08	22.06	13:42	22.20	22.15	22.18	22.13	14:42	22.01	21.89	21.99	21.87
12:43	22.15	22.08	22.11	22.08	13:43	22.23	22.18	22.18	22.15	14:43	21.99	21.89	21.96	21.84
12:44	22.18	22.11	22.13	22.11	13:44	22.23	22.18	22.20	22.18	14:44	21.94	21.84	21.94	21.82
12:45	22.18	22.11	22.13	22.11	13:45	22.25	22.18	22.20	22.18	14:45	21.94	21.84	21.94	21.80
12:46	22.18	22.08	22.11	22.06	13:46	22.23	22.15	22.20	22.13	14:46	21.92	21.84	21.92	21.80
12:47	22.13	22.01	22.08	22.01	13:47	22.15	22.08	22.13	22.03	14:47	21.96	21.92	21.94	21.87
12:48	22.08	21.99	22.06	21.96	13:48	22.11	22.03	22.11	22.01	14:48	22.01	21.94	21.96	21.92
12:49	22.06	21.96	22.03	21.94	13:49	22.11	22.01	22.08	21.99	14:49	22.03	21.96	21.99	21.94
12:50	22.03	21.96	22.01	21.92	13:50	22.06	21.96	22.06	21.92	14:50	22.06	22.01	22.03	21.99
12:51	22.01	21.94	22.01	21.92	13:51	22.03	21.94	22.03	21.92	14:51	22.11	22.03	22.06	22.03
12:52	22.01	21.96	22.01	21.92	13:52	22.01	21.92	22.01	21.87	14:52	22.13	22.08	22.08	22.06
12:53	22.01	21.94	22.01	21.92	13:53	21.99	21.92	21.99	21.87	14:53	22.13	22.06	22.08	22.03
12:54	22.01	21.94	22.01	21.92	13:54	21.99	21.92	21.99	21.87	14:54	22.08	21.99	22.03	21.96
12:55	22.03	21.99	22.01	21.94	13:55	21.96	21.89	21.96	21.84	14:55	22.03	21.96	22.01	21.92
12:56	22.06	22.01	22.03	21.99	13:56	21.96	21.87	21.96	21.82	14:56	21.99	21.92	21.99	21.84
12:57	22.08	22.01	22.06	21.99	13:57	21.96	21.89	21.96	21.84	14:57	21.96	21.92	21.96	21.82
12:58	22.11	22.06	22.08	22.03	13:58	21.94	21.87	21.94	21.80	14:58	21.94	21.87	21.96	21.77
12:59	22.13	22.06	22.08	22.06	13:59	21.94	21.87	21.94	21.80	14:59	21.92	21.87	21.94	21.75

16th Hour: Calibration Test					17th Hour: Calibration Test					18th Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
15:00	21.94	21.89	21.96	21.80	16:00	22.23	22.13	22.18	22.06	17:00	21.94	21.87	21.94	21.80
15:01	21.96	21.92	21.96	21.84	16:01	22.13	22.03	22.11	21.96	17:01	21.96	21.92	21.96	21.84
15:02	22.01	21.96	22.01	21.89	16:02	22.06	21.96	22.06	21.89	17:02	22.01	21.96	21.99	21.92
15:03	22.03	21.99	22.03	21.94	16:03	22.03	21.96	22.03	21.92	17:03	22.06	22.01	22.03	21.94
15:04	22.08	22.03	22.06	21.99	16:04	22.03	21.94	22.03	21.89	17:04	22.06	21.99	22.03	21.89
15:05	22.13	22.08	22.11	22.06	16:05	21.99	21.92	21.99	21.82	17:05	21.99	21.92	21.99	21.80
15:06	22.15	22.11	22.13	22.06	16:06	21.96	21.92	21.99	21.82	17:06	21.92	21.87	21.94	21.72
15:07	22.18	22.13	22.13	22.08	16:07	22.01	21.96	22.01	21.87	17:07	21.87	21.80	21.92	21.70
15:08	22.15	22.08	22.13	22.01	16:08	22.06	22.01	22.03	21.94	17:08	21.84	21.77	21.87	21.68
15:09	22.08	21.99	22.08	21.94	16:09	22.11	22.03	22.06	21.99	17:09	21.87	21.82	21.89	21.72
15:10	22.06	21.99	22.06	21.94	16:10	22.13	22.08	22.11	22.03	17:10	21.92	21.87	21.92	21.77
15:11	22.06	22.01	22.06	21.94	16:11	22.13	22.03	22.11	21.99	17:11	21.96	21.92	21.94	21.87
15:12	22.08	22.01	22.06	21.96	16:12	22.06	22.01	22.06	21.92	17:12	22.01	21.96	21.99	21.92
15:13	22.08	22.01	22.08	21.99	16:13	22.06	22.01	22.06	21.96	17:13	22.03	21.96	22.01	21.92
15:14	22.11	22.03	22.08	22.01	16:14	22.08	22.01	22.06	21.99	17:14	22.03	21.96	22.01	21.92
15:15	22.08	21.99	22.06	21.94	16:15	22.11	22.03	22.08	21.99	17:15	22.03	21.99	22.01	21.94
15:16	22.03	21.96	22.03	21.87	16:16	22.11	22.03	22.08	22.01	17:16	22.03	21.99	22.01	21.92
15:17	21.99	21.94	22.01	21.84	16:17	22.11	22.03	22.08	21.99	17:17	22.03	21.96	22.01	21.92
15:18	22.01	21.94	21.99	21.87	16:18	22.11	22.03	22.08	21.99	17:18	22.01	21.94	21.99	21.87
15:19	22.03	21.99	22.01	21.92	16:19	22.08	22.01	22.08	21.96	17:19	21.99	21.92	21.99	21.84
15:20	22.06	22.01	22.03	21.96	16:20	22.06	21.99	22.06	21.92	17:20	21.94	21.87	21.94	21.77
15:21	22.11	22.06	22.06	22.01	16:21	22.03	21.96	22.03	21.89	17:21	21.92	21.87	21.94	21.75
15:22	22.11	22.03	22.08	22.01	16:22	22.03	21.99	22.03	21.92	17:22	21.92	21.82	21.92	21.75
15:23	22.11	22.03	22.08	21.99	16:23	22.03	21.99	22.03	21.89	17:23	21.89	21.82	21.92	21.75
15:24	22.11	22.06	22.08	21.99	16:24	22.06	22.01	22.03	21.92	17:24	21.89	21.82	21.92	21.77
15:25	22.13	22.06	22.11	22.03	16:25	22.08	22.06	22.06	21.96	17:25	21.89	21.82	21.92	21.75
15:26	22.11	22.03	22.08	21.99	16:26	22.08	22.03	22.08	21.96	17:26	21.89	21.84	21.92	21.72
15:27	22.06	21.99	22.06	21.92	16:27	22.08	22.03	22.06	21.96	17:27	21.89	21.84	21.92	21.72
15:28	22.01	21.96	22.03	21.87	16:28	22.08	22.03	22.06	21.96	17:28	21.89	21.82	21.92	21.75
15:29	22.01	21.96	22.01	21.87	16:29	22.11	22.03	22.08	21.99	17:29	21.89	21.82	21.89	21.72
15:30	22.01	21.96	22.01	21.89	16:30	22.11	22.06	22.08	22.01	17:30	21.87	21.84	21.89	21.72
15:31	22.03	21.99	22.03	21.94	16:31	22.13	22.06	22.11	22.03	17:31	21.89	21.84	21.92	21.72
15:32	22.06	22.03	22.06	21.96	16:32	22.15	22.08	22.13	22.03	17:32	21.87	21.82	21.89	21.70
15:33	22.08	22.03	22.06	21.96	16:33	22.13	22.03	22.11	21.99	17:33	21.87	21.82	21.87	21.70
15:34	22.03	21.99	22.03	21.92	16:34	22.11	22.03	22.08	21.99	17:34	21.84	21.82	21.87	21.72
15:35	22.03	21.96	22.03	21.92	16:35	22.11	22.06	22.08	22.01	17:35	21.87	21.82	21.87	21.72
15:36	22.03	21.99	22.03	21.94	16:36	22.13	22.06	22.11	22.01	17:36	21.87	21.80	21.87	21.70
15:37	22.06	22.01	22.06	21.94	16:37	22.08	21.99	22.06	21.96	17:37	21.82	21.80	21.87	21.68
15:38	22.08	22.03	22.06	21.99	16:38	22.06	21.99	22.06	21.94	17:38	21.84	21.80	21.87	21.70
15:39	22.11	22.06	22.08	22.01	16:39	22.06	21.99	22.03	21.92	17:39	21.84	21.80	21.87	21.70
15:40	22.13	22.06	22.11	22.03	16:40	22.06	21.99	22.06	21.94	17:40	21.84	21.75	21.87	21.68
15:41	22.11	22.03	22.08	22.01	16:41	22.06	21.96	22.03	21.89	17:41	21.82	21.75	21.84	21.68
15:42	22.08	22.01	22.08	21.96	16:42	21.99	21.89	21.99	21.80	17:42	21.82	21.75	21.84	21.68
15:43	22.06	21.99	22.06	21.96	16:43	21.92	21.84	21.94	21.77	17:43	21.84	21.77	21.84	21.72
15:44	22.03	21.99	22.03	21.92	16:44	21.94	21.87	21.94	21.80	17:44	21.84	21.80	21.84	21.70
15:45	22.01	21.94	22.01	21.87	16:45	21.99	21.92	21.99	21.87	17:45	21.84	21.80	21.84	21.68
15:46	21.99	21.94	22.01	21.84	16:46	21.99	21.92	21.99	21.84	17:46	21.84	21.77	21.84	21.68
15:47	21.96	21.89	21.99	21.82	16:47	21.99	21.94	22.01	21.89	17:47	21.87	21.82	21.84	21.70
15:48	21.94	21.84	21.96	21.77	16:48	22.01	21.96	22.01	21.89	17:48	21.84	21.80	21.84	21.68
15:49	21.94	21.87	21.96	21.82	16:49	22.01	21.92	22.01	21.87	17:49	21.84	21.80	21.84	21.68
15:50	21.99	21.94	22.01	21.92	16:50	21.96	21.89	21.96	21.82	17:50	21.84	21.77	21.84	21.68
15:51	22.03	21.99	22.03	21.94	16:51	21.94	21.84	21.94	21.77	17:51	21.84	21.80	21.84	21.70
15:52	22.08	22.03	22.06	21.99	16:52	21.94	21.87	21.94	21.80	17:52	21.84	21.77	21.84	21.68
15:53	22.13	22.08	22.11	22.03	16:53	21.96	21.92	21.96	21.87	17:53	21.82	21.77	21.82	21.65
15:54	22.18	22.13	22.13	22.08	16:54	22.01	21.94	21.99	21.92	17:54	21.84	21.75	21.84	21.68
15:55	22.20	22.18	22.15	22.11	16:55	22.06	22.01	22.03	21.96	17:55	21.84	21.77	21.84	21.68
15:56	22.23	22.18	22.18	22.11	16:56	22.08	22.01	22.06	21.99	17:56	21.84	21.77	21.84	21.70
15:57	22.25	22.20	22.18	22.13	16:57	22.06	21.99	22.03	21.92	17:57	21.84	21.77	21.84	21.68
15:58	22.25	22.20	22.20	22.15	16:58	21.96	21.89	21.99	21.80	17:58	21.82	21.77	21.82	21.65
15:59	22.25	22.20	22.20	22.15	16:59	21.94	21.87	21.96	21.80	17:59	21.82	21.77	21.82	21.65

19th Hour: Calibration Test					20th Hour: Calibration Test					21st Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
18:00	21.80	21.75	21.82	21.63	19:00	21.99	21.94	21.99	21.87	20:00	21.80	21.72	21.82	21.63
18:01	21.82	21.77	21.84	21.68	19:01	21.99	21.92	21.99	21.82	20:01	21.80	21.75	21.82	21.63
18:02	21.84	21.80	21.84	21.68	19:02	21.96	21.92	21.99	21.82	20:02	21.82	21.77	21.84	21.68
18:03	21.87	21.82	21.87	21.72	19:03	21.92	21.84	21.92	21.72	20:03	21.84	21.77	21.84	21.68
18:04	21.87	21.82	21.87	21.70	19:04	21.92	21.87	21.94	21.75	20:04	21.84	21.77	21.84	21.68
18:05	21.87	21.80	21.87	21.70	19:05	21.94	21.92	21.96	21.82	20:05	21.84	21.77	21.84	21.68
18:06	21.87	21.80	21.87	21.70	19:06	21.96	21.94	21.99	21.87	20:06	21.82	21.72	21.84	21.65
18:07	21.84	21.77	21.84	21.65	19:07	22.01	21.96	22.01	21.92	20:07	21.82	21.75	21.82	21.65
18:08	21.84	21.80	21.84	21.68	19:08	22.03	22.01	22.06	21.94	20:08	21.82	21.75	21.84	21.65
18:09	21.84	21.80	21.87	21.68	19:09	22.03	21.99	22.06	21.92	20:09	21.82	21.77	21.84	21.65
18:10	21.84	21.77	21.84	21.65	19:10	21.99	21.94	22.01	21.84	20:10	21.82	21.75	21.82	21.65
18:11	21.84	21.80	21.87	21.68	19:11	21.99	21.94	22.01	21.84	20:11	21.84	21.80	21.84	21.70
18:12	21.82	21.77	21.84	21.68	19:12	21.99	21.92	22.01	21.84	20:12	21.87	21.84	21.87	21.75
18:13	21.82	21.75	21.84	21.65	19:13	21.96	21.92	21.99	21.80	20:13	21.92	21.87	21.89	21.77
18:14	21.82	21.77	21.84	21.65	19:14	21.92	21.87	21.96	21.77	20:14	21.94	21.92	21.92	21.82
18:15	21.82	21.77	21.84	21.68	19:15	21.87	21.82	21.92	21.70	20:15	21.99	21.94	21.94	21.84
18:16	21.82	21.77	21.84	21.65	19:16	21.82	21.75	21.87	21.63	20:16	22.01	21.96	21.96	21.89
18:17	21.82	21.80	21.84	21.65	19:17	21.77	21.68	21.82	21.58	20:17	22.03	22.01	21.99	21.92
18:18	21.84	21.80	21.87	21.68	19:18	21.77	21.72	21.80	21.58	20:18	22.08	22.06	22.03	21.96
18:19	21.84	21.80	21.87	21.70	19:19	21.80	21.72	21.82	21.60	20:19	22.11	22.06	22.06	21.96
18:20	21.87	21.82	21.87	21.72	19:20	21.82	21.75	21.82	21.60	20:20	22.11	22.06	22.06	21.99
18:21	21.84	21.80	21.87	21.70	19:21	21.80	21.72	21.80	21.60	20:21	22.13	22.08	22.08	22.03
18:22	21.87	21.82	21.87	21.75	19:22	21.80	21.75	21.80	21.63	20:22	22.15	22.11	22.11	22.03
18:23	21.92	21.89	21.92	21.82	19:23	21.82	21.75	21.82	21.63	20:23	22.15	22.08	22.11	22.03
18:24	21.96	21.92	21.94	21.84	19:24	21.80	21.72	21.82	21.60	20:24	22.15	22.11	22.13	22.06
18:25	22.01	21.96	21.96	21.92	19:25	21.82	21.75	21.82	21.63	20:25	22.18	22.13	22.13	22.08
18:26	22.03	21.99	21.99	21.94	19:26	21.82	21.77	21.82	21.65	20:26	22.18	22.15	22.15	22.11
18:27	22.08	22.03	22.03	21.99	19:27	21.84	21.77	21.82	21.65	20:27	22.20	22.15	22.18	22.11
18:28	22.11	22.06	22.06	22.01	19:28	21.84	21.77	21.82	21.68	20:28	22.18	22.13	22.15	22.06
18:29	22.13	22.08	22.08	22.06	19:29	21.84	21.77	21.84	21.68	20:29	22.13	22.06	22.13	21.99
18:30	22.15	22.11	22.11	22.06	19:30	21.82	21.77	21.84	21.65	20:30	22.03	21.99	22.06	21.87
18:31	22.18	22.13	22.13	22.08	19:31	21.82	21.75	21.82	21.65	20:31	21.94	21.84	22.01	21.77
18:32	22.18	22.13	22.13	22.08	19:32	21.82	21.75	21.82	21.65	20:32	21.87	21.80	21.94	21.70
18:33	22.18	22.13	22.15	22.08	19:33	21.82	21.72	21.82	21.63	20:33	21.82	21.72	21.87	21.63
18:34	22.18	22.13	22.15	22.11	19:34	21.82	21.75	21.80	21.63	20:34	21.80	21.68	21.84	21.60
18:35	22.20	22.18	22.18	22.13	19:35	21.80	21.75	21.80	21.63	20:35	21.77	21.68	21.82	21.58
18:36	22.23	22.18	22.18	22.13	19:36	21.80	21.75	21.80	21.60	20:36	21.75	21.68	21.80	21.58
18:37	22.23	22.18	22.18	22.15	19:37	21.80	21.75	21.82	21.60	20:37	21.77	21.70	21.82	21.60
18:38	22.20	22.13	22.15	22.11	19:38	21.82	21.75	21.82	21.63	20:38	21.75	21.65	21.80	21.58
18:39	22.15	22.03	22.11	22.01	19:39	21.82	21.75	21.82	21.63	20:39	21.75	21.68	21.80	21.58
18:40	22.08	22.01	22.06	21.96	19:40	21.82	21.77	21.82	21.65	20:40	21.75	21.65	21.80	21.56
18:41	22.06	21.99	22.06	21.94	19:41	21.84	21.77	21.82	21.65	20:41	21.75	21.65	21.80	21.58
18:42	22.03	21.94	22.01	21.89	19:42	21.82	21.75	21.84	21.65	20:42	21.80	21.70	21.80	21.60
18:43	22.01	21.92	21.99	21.87	19:43	21.84	21.75	21.84	21.65	20:43	21.80	21.72	21.80	21.60
18:44	21.99	21.94	21.99	21.87	19:44	21.84	21.72	21.84	21.68	20:44	21.82	21.75	21.82	21.63
18:45	22.01	21.94	22.01	21.87	19:45	21.84	21.75	21.84	21.65	20:45	21.82	21.75	21.82	21.65
18:46	22.01	21.94	21.99	21.87	19:46	21.80	21.70	21.82	21.63	20:46	21.84	21.77	21.82	21.65
18:47	21.99	21.92	21.99	21.84	19:47	21.80	21.70	21.82	21.63	20:47	21.84	21.77	21.84	21.68
18:48	21.99	21.94	22.01	21.87	19:48	21.80	21.68	21.82	21.60	20:48	21.84	21.80	21.84	21.68
18:49	22.01	21.94	22.01	21.87	19:49	21.80	21.70	21.82	21.63	20:49	21.84	21.77	21.87	21.70
18:50	22.01	21.94	22.01	21.87	19:50	21.80	21.70	21.82	21.65	20:50	21.84	21.77	21.84	21.70
18:51	21.99	21.92	21.99	21.87	19:51	21.82	21.72	21.82	21.68	20:51	21.82	21.77	21.84	21.68
18:52	22.01	21.94	21.99	21.87	19:52	21.84	21.75	21.84	21.68	20:52	21.82	21.75	21.82	21.65
18:53	22.01	21.94	22.01	21.87	19:53	21.84	21.75	21.84	21.68	20:53	21.80	21.75	21.82	21.68
18:54	21.99	21.96	22.01	21.84	19:54	21.84	21.75	21.84	21.65	20:54	21.82	21.75	21.84	21.68
18:55	21.99	21.94	22.01	21.82	19:55	21.84	21.77	21.84	21.68	20:55	21.82	21.75	21.82	21.65
18:56	21.99	21.94	21.99	21.82	19:56	21.82	21.75	21.84	21.68	20:56	21.82	21.80	21.84	21.65
18:57	21.99	21.94	21.99	21.87	19:57	21.84	21.75	21.84	21.68	20:57	21.82	21.80	21.84	21.65
18:58	21.99	21.94	21.99	21.87	19:58	21.82	21.72	21.84	21.65	20:58	21.82	21.75	21.84	21.65
18:59	21.99	21.94	21.99	21.84	19:59	21.82	21.75	21.84	21.65	20:59	21.82	21.75	21.84	21.65

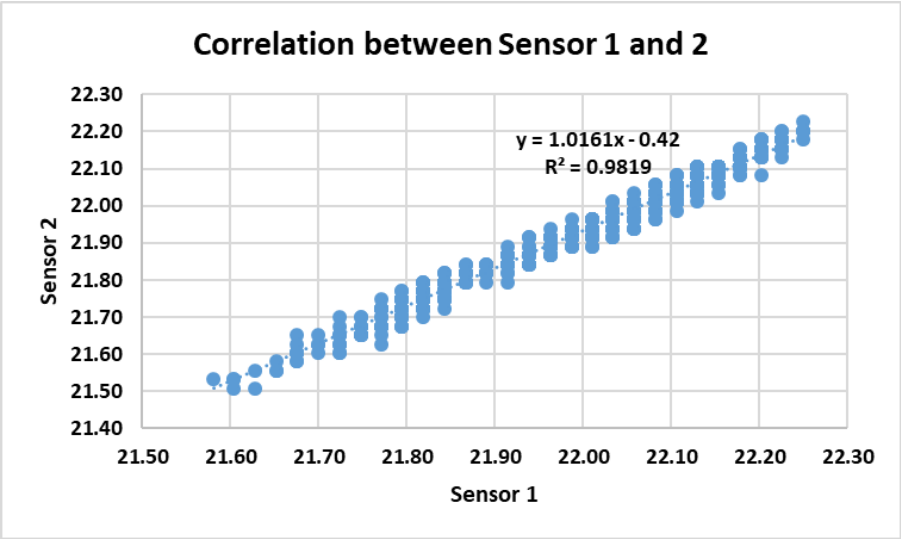
22nd Hour: Calibration Test					23rd Hour: Calibration Test					24th Hour: Calibration Test				
Time	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Time**	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
21:00	21.80	21.72	21.82	21.63	22:00	21.82	21.75	21.84	21.65	23:00	22.03	21.94	22.06	21.84
21:01	21.82	21.75	21.84	21.65	22:01	21.82	21.75	21.82	21.68	23:01	21.94	21.87	21.99	21.75
21:02	21.82	21.75	21.84	21.65	22:02	21.82	21.75	21.82	21.65	23:02	21.89	21.82	21.94	21.68
21:03	21.84	21.77	21.84	21.68	22:03	21.80	21.75	21.84	21.63	23:03	21.84	21.77	21.92	21.63
21:04	21.84	21.75	21.82	21.68	22:04	21.80	21.75	21.82	21.63	23:04	21.80	21.72	21.87	21.60
21:05	21.84	21.77	21.84	21.70	22:05	21.77	21.72	21.80	21.60	23:05	21.80	21.72	21.84	21.58
21:06	21.84	21.77	21.84	21.68	22:06	21.80	21.75	21.82	21.58	23:06	21.77	21.68	21.82	21.56
21:07	21.82	21.77	21.84	21.68	22:07	21.77	21.75	21.82	21.60	23:07	21.75	21.65	21.80	21.53
21:08	21.82	21.75	21.84	21.65	22:08	21.80	21.77	21.82	21.60	23:08	21.72	21.65	21.77	21.51
21:09	21.82	21.75	21.82	21.65	22:09	21.80	21.77	21.82	21.60	23:09	21.72	21.65	21.77	21.51
21:10	21.82	21.77	21.84	21.63	22:10	21.80	21.72	21.82	21.60	23:10	21.72	21.63	21.75	21.53
21:11	21.84	21.77	21.84	21.68	22:11	21.80	21.75	21.82	21.63	23:11	21.72	21.63	21.75	21.53
21:12	21.84	21.77	21.84	21.65	22:12	21.82	21.75	21.82	21.65	23:12	21.75	21.65	21.77	21.56
21:13	21.84	21.77	21.84	21.65	22:13	21.82	21.77	21.82	21.65	23:13	21.77	21.72	21.80	21.60
21:14	21.84	21.80	21.84	21.68	22:14	21.82	21.77	21.82	21.65	23:14	21.80	21.75	21.82	21.63
21:15	21.84	21.82	21.87	21.68	22:15	21.82	21.77	21.82	21.65	23:15	21.80	21.72	21.82	21.63
21:16	21.84	21.82	21.87	21.68	22:16	21.84	21.80	21.84	21.68	23:16	21.80	21.72	21.82	21.63
21:17	21.87	21.80	21.84	21.68	22:17	21.84	21.80	21.84	21.68	23:17	21.80	21.72	21.82	21.65
21:18	21.87	21.80	21.87	21.68	22:18	21.84	21.80	21.87	21.70	23:18	21.82	21.77	21.82	21.68
21:19	21.84	21.80	21.87	21.68	22:19	21.84	21.77	21.84	21.68	23:19	21.84	21.77	21.84	21.70
21:20	21.87	21.80	21.87	21.68	22:20	21.84	21.80	21.84	21.68	23:20	21.84	21.77	21.84	21.70
21:21	21.87	21.82	21.87	21.70	22:21	21.84	21.77	21.87	21.68	23:21	21.84	21.77	21.84	21.68
21:22	21.89	21.84	21.87	21.72	22:22	21.82	21.77	21.84	21.68	23:22	21.84	21.75	21.84	21.65
21:23	21.92	21.84	21.92	21.77	22:23	21.84	21.77	21.84	21.68	23:23	21.82	21.72	21.84	21.65
21:24	21.96	21.92	21.92	21.82	22:24	21.84	21.80	21.84	21.68	23:24	21.80	21.72	21.82	21.63
21:25	22.01	21.96	21.96	21.87	22:25	21.84	21.80	21.84	21.68	23:25	21.80	21.72	21.82	21.63
21:26	22.06	22.01	21.99	21.92	22:26	21.84	21.77	21.84	21.68	23:26	21.82	21.75	21.82	21.65
21:27	22.08	22.06	22.03	21.94	22:27	21.84	21.80	21.84	21.68	23:27	21.82	21.75	21.82	21.68
21:28	22.11	22.06	22.06	21.96	22:28	21.84	21.80	21.84	21.65	23:28	21.84	21.80	21.84	21.70
21:29	22.11	22.08	22.08	21.99	22:29	21.84	21.80	21.87	21.65	23:29	21.87	21.82	21.87	21.70
21:30	22.13	22.11	22.08	22.01	22:30	21.84	21.77	21.87	21.65	23:30	21.84	21.77	21.87	21.70
21:31	22.18	22.15	22.13	22.06	22:31	21.82	21.75	21.84	21.63	23:31	21.84	21.75	21.84	21.68
21:32	22.20	22.18	22.15	22.08	22:32	21.80	21.72	21.82	21.63	23:32	21.82	21.72	21.84	21.68
21:33	22.20	22.18	22.15	22.11	22:33	21.80	21.75	21.82	21.65	23:33	21.82	21.72	21.84	21.68
21:34	22.23	22.20	22.18	22.13	22:34	21.80	21.75	21.82	21.65	23:34	21.82	21.72	21.84	21.68
21:35	22.25	22.23	22.20	22.15	22:35	21.82	21.72	21.82	21.63	23:35	21.82	21.75	21.82	21.63
21:36	22.25	22.20	22.20	22.15	22:36	21.80	21.72	21.82	21.63	23:36	21.82	21.77	21.84	21.65
21:37	22.23	22.15	22.20	22.11	22:37	21.80	21.75	21.82	21.63	23:37	21.84	21.77	21.84	21.65
21:38	22.18	22.11	22.15	22.06	22:38	21.80	21.72	21.82	21.63	23:38	21.82	21.77	21.84	21.65
21:39	22.11	22.03	22.11	21.94	22:39	21.77	21.72	21.80	21.60	23:39	21.82	21.75	21.84	21.63
21:40	22.01	21.94	22.03	21.84	22:40	21.80	21.75	21.80	21.63	23:40	21.82	21.72	21.84	21.63
21:41	21.94	21.87	21.99	21.75	22:41	21.80	21.72	21.80	21.63	23:41	21.80	21.70	21.82	21.63
21:42	21.92	21.84	21.94	21.70	22:42	21.82	21.75	21.82	21.63	23:42	21.80	21.72	21.82	21.63
21:43	21.89	21.80	21.92	21.68	22:43	21.84	21.80	21.82	21.70	23:43	21.82	21.72	21.82	21.65
21:44	21.82	21.72	21.89	21.63	22:44	21.92	21.87	21.89	21.75	23:44	21.80	21.72	21.82	21.63
21:45	21.82	21.75	21.87	21.63	22:45	21.94	21.92	21.92	21.80	23:45	21.80	21.72	21.82	21.65
21:46	21.80	21.72	21.84	21.60	22:46	21.99	21.94	21.94	21.84	23:46	21.82	21.75	21.82	21.68
21:47	21.80	21.70	21.82	21.63	22:47	22.01	21.96	21.99	21.89	23:47	21.82	21.72	21.82	21.65
21:48	21.80	21.70	21.82	21.60	22:48	22.06	22.01	22.01	21.94	23:48	21.82	21.72	21.82	21.65
21:49	21.80	21.70	21.80	21.58	22:49	22.08	22.01	22.03	21.94	23:49	21.80	21.72	21.82	21.65
21:50	21.77	21.65	21.80	21.56	22:50	22.11	22.06	22.06	21.99	23:50	21.82	21.75	21.82	21.68
21:51	21.75	21.65	21.77	21.53	22:51	22.13	22.08	22.08	22.01	23:51	21.84	21.77	21.84	21.68
21:52	21.75	21.65	21.77	21.56	22:52	22.15	22.11	22.11	22.03	23:52	21.84	21.80	21.84	21.68
21:53	21.75	21.68	21.77	21.56	22:53	22.15	22.11	22.11	22.03	23:53	21.84	21.77	21.84	21.65
21:54	21.77	21.68	21.77	21.58	22:54	22.15	22.11	22.13	22.06	23:54	21.84	21.80	21.87	21.68
21:55	21.80	21.70	21.77	21.60	22:55	22.18	22.13	22.15	22.06	23:55	21.87	21.82	21.87	21.70
21:56	21.80	21.68	21.80	21.60	22:56	22.20	22.15	22.15	22.11	23:56	21.87	21.80	21.87	21.70
21:57	21.80	21.70	21.80	21.60	22:57	22.23	22.20	22.18	22.13	23:57	21.87	21.80	21.87	21.70
21:58	21.82	21.75	21.82	21.65	22:58	22.23	22.15	22.18	22.11	23:58	21.84	21.80	21.87	21.70
21:59	21.84	21.75	21.84	21.65	22:59	22.15	22.08	22.13	21.99	23:59	21.84	21.80	21.87	21.68

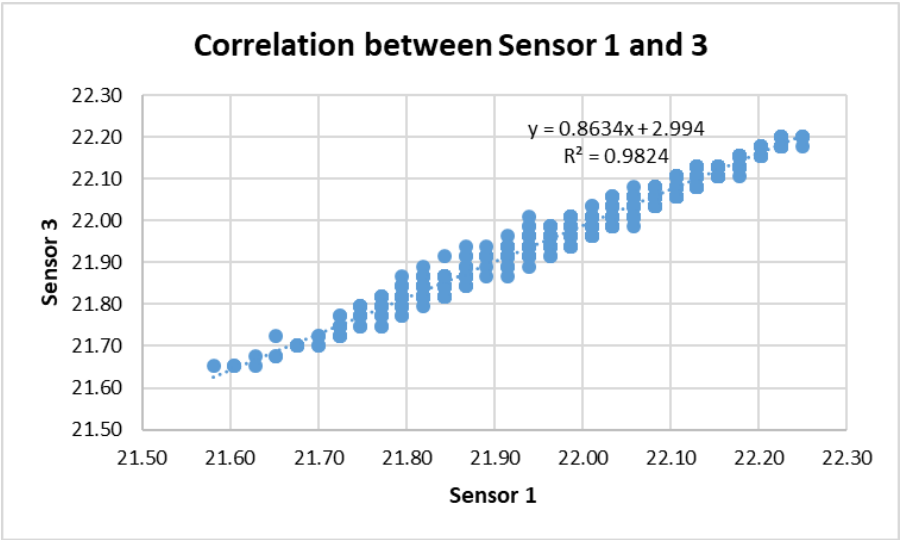
9.2 Appendix B – Calibration Test of Sensors

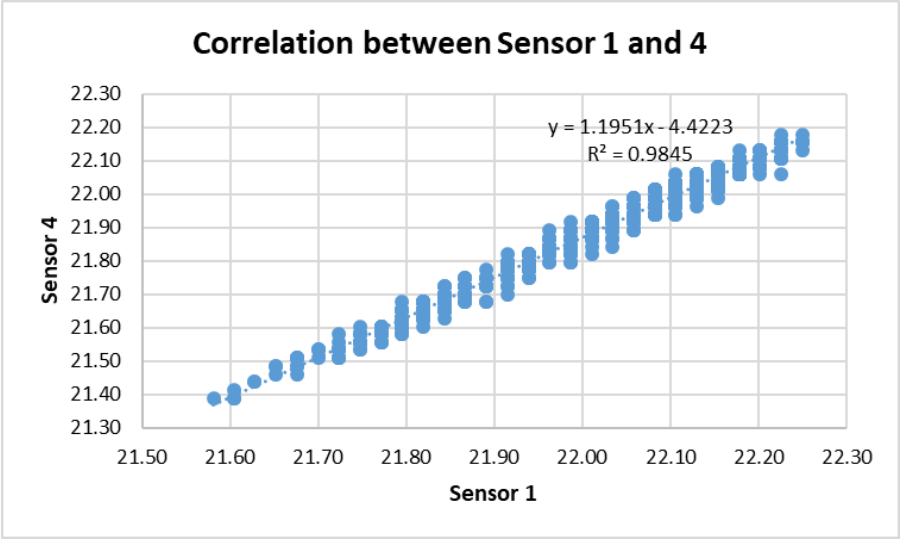


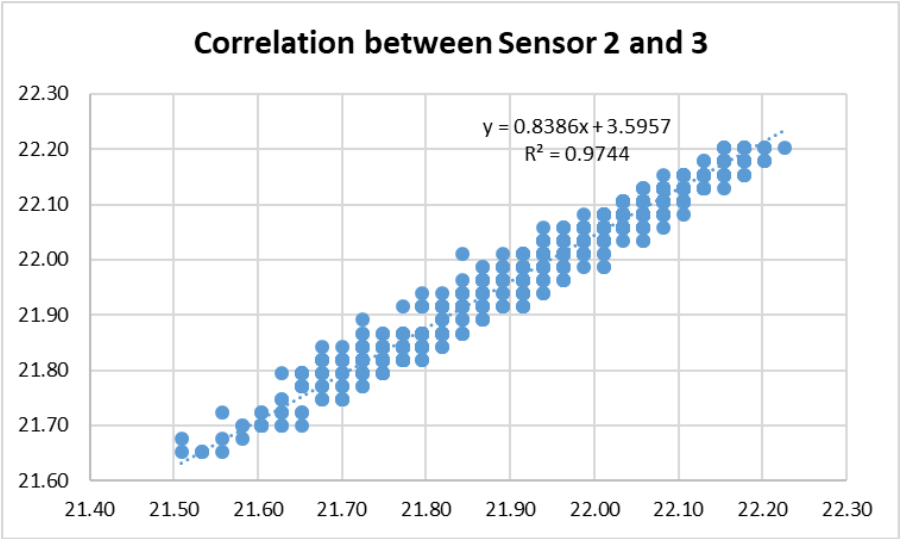
9.3 Appendix C – Correlation Between Sensors

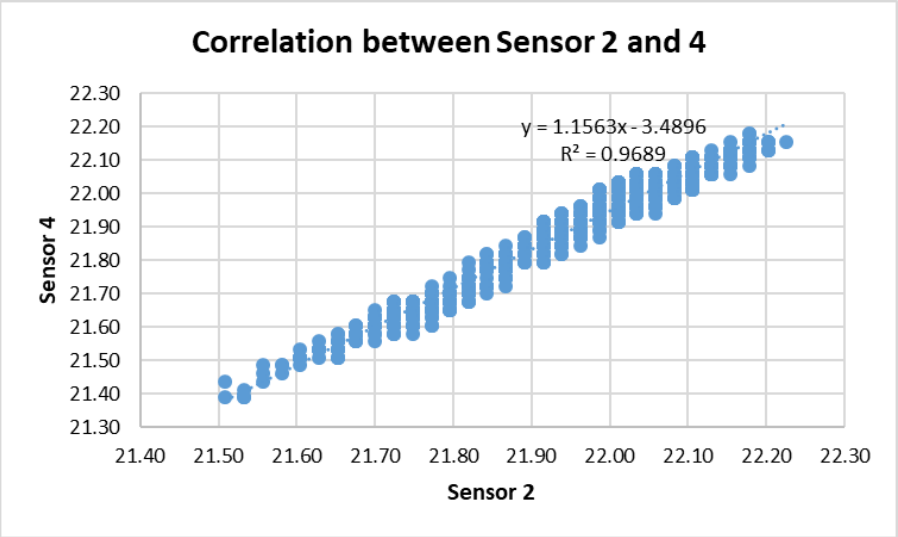
Correlation between sensors				
	Sensor 1	***Sensor 2***	***Sensor 3***	***Sensor 4***
Sensor 1	1			
Sensor 2	0.990930426	1		
Sensor 3	0.991179994	0.987133374	1	
Sensor 4	0.992239456	0.98432119	0.981007496	1

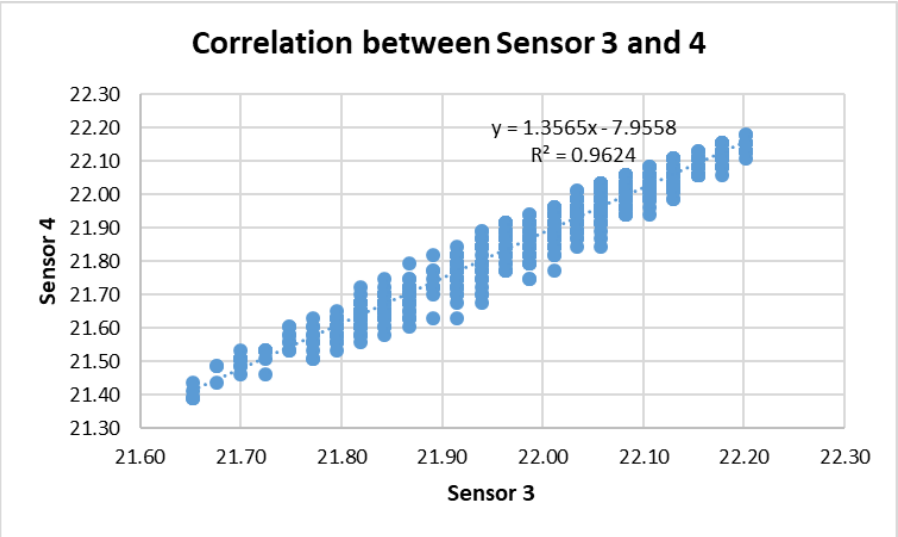



Correlation between Sensor 1 and 3
y = 0.8634x + 2.994
R² = 0.9824
Sensor 3
Sensor 1
22.30
22.20
22.10
22.00
21.90
21.80
21.70
21.60
21.50
21.50
21.60
21.70
21.80
21.90
22.00
22.10
22.20
22.30


Correlation between Sensor 1 and 4
y = 1.1951x - 4.4223
R² = 0.9845
Sensor 4
Sensor 1
22.30
22.20
22.10
22.00
21.90
21.80
21.70
21.60
21.50
21.40
21.30
21.50
21.60
21.70
21.80
21.90
22.00
22.10
22.20
22.30


Correlation between Sensor 2 and 3
y = 0.8386x + 3.5957
R² = 0.9744
22.30
22.20
22.10
22.00
21.90
21.80
21.70
21.60
21.40
21.50
21.60
21.70
21.80
21.90
22.00
22.10
22.20
22.30

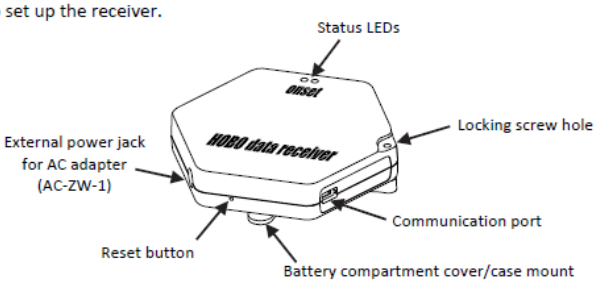

Correlation between Sensor 2 and 4
y = 1.1563x - 3.4896
R² = 0.9689
Sensor 4
Sensor 2
22.30
22.20
22.10
22.00
21.90
21.80
21.70
21.60
21.50
21.40
21.30
21.40
21.50
21.60
21.70
21.80
21.90
22.00
22.10
22.20
22.30

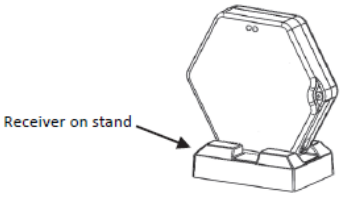

Correlation between Sensor 3 and 4
y = 1.3565x - 7.9558
R² = 0.9624
Sensor 4
Sensor 3
22.30
22.20
22.10
22.00
21.90
21.80
21.70
21.60
21.50
21.40
21.30
21.60
21.70
21.80
21.90
22.00
22.10
22.20
22.30

9.4 APPENDIX D – DATA RECEIVER

HOBO® Data Receiver (ZW-RCVR)

The HOBO data receiver (ZW-RCVR) collects data transmitted from nodes in the ZW series wireless network and uploads it to a computer running HOBOware® 3.0 or later. The receiver forms the network, stores network information, and relays configuration commands to the data nodes. Refer to the *HOBO ZW Series Wireless Network Quick Start Guide* for information on how to set up the receiver.





HOBO Data Receiver (ZW-RCVR)

Included Items:

- AC adapter (AC-ZW-1)
- 3 AAA batteries
- 1 locking screw
- Adhesive label
- Stand
- HOBOware software
- USB cable
- Quick Start Guide

Specifications

Radio power	1.6 mW (2 dBm)
Transmission range	Approx. 100 m (328 ft), depending on obstructions or interference
Wireless data standard	IEEE 802.15.4, 2.4 GHz band
Operating Temperature	-20° to 50°C (-4° to 122°F) when battery powered, -20° to 70°C (-4° to 158°F) when line powered
Operating RH	5% to 95% non-condensing
Communication to PC	USB cable
Power options	AC power adapter (AC-ZW-1): Input: 100–240 V at 50/60 Hz 0.20 A Output: 6 VDC at 0.5 A Batteries (as backup power): 3 alkaline AAA USB powered: Powered by USB port connection to a computer
Battery life	Approximately 19 hours
Maximum number of nodes	100
Time accuracy	± 1 minute per month at 25°C (77°F)
Memory capacity	3.7 MB
Case material	ABS
Dimensions	96.5 x 108 x 28 mm (3.8 x 4.25 x 1.1 in.)
Weight (with batteries)	138 g (4.87 oz)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).
FC	See reverse side

13663-C MAN-ZW-RCVR

FCC Compliance

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one of the following measures:

- Reorient or relocate the receiving antenna
- Increase the separation between the equipment and receiver
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected
- Consult the dealer or an experienced radio/TV technician for help

Changes or modifications not expressly approved by Onset Computer Corporation could void the user's authority to operate the equipment.

To comply with FCC and Industry Canada RF radiation exposure limits for general population, the HOBO data nodes, receivers, and routers must be installed to provide a separation distance of at least 20cm from all persons and must not be co-located or operating in conjunction with any other antenna or transmitter.

Canada

This device has been designed to operate with the antenna listed below, and having a maximum gain of 1 dB. Antennas not included in this list or having a gain greater than 1 dB are strictly prohibited for use with this device. The required antenna impedance is 50 ohms.

To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that permitted for successful communication.

Approved antenna: Johanson Technologies P/N 2450AT45A100 1.0 dBi chip antenna

FCC Declaration of Conformity

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

onset®

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www.onsetcomp.com • loggerhelp@onsetcomp.com

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13663-C MAN-ZW-RCVR

9.5 APPENDIX E – SPECIFICATIONS OF SENSORS

ONSET

HOBO® ZW Series Wireless Sensors

Monitor and transmit real-time building performance data… wirelessly!

HOBO ZW Series wireless data nodes provide centralized monitoring of energy and environmental conditions in buildings.

monitor not included

Supported Measurements: Air Velocity, AC Current, AC Voltage, Amp Hour, $C0_2$, Compressed Air Flow, DC Current, DC Voltage, Differential Pressure, Gauge Pressure, Kilowatt Hours, Kilowatts, Power Factor, Pulse Signals, Temperature, Relative Humidity, Dew Point, Volatile Organic Compound, Volt-Amp Reactive, Volt-Amp Reactive Hour, Volt-Amps, Water Flow, Watt Hours, Watts, Volts, Amps, 0-10 VDC, 4-20mA

Key Advantages:

- Provides real-time centralized data collection within a facility
- Scales up to a network of 100 nodes sending data to a single receiver
- Creates self-healing network to overcome obstructions in communication paths
- Provides one year battery life @ 15-minute logging intervals
- Provides alarm notifications via email or text messages
- Features powerful software for organizing and viewing data as well as the wireless network

For complete information and accessories, please visit: **www.onsetcomp.com**

Part number	ZW-RCVR (Receiver)	ZW-001 (Data node)	ZW-003* (Data node)	ZW-005* (Data node)	ZW-006 (Data node)	ZW-007* (Data node)	ZW-008 (Data node)	ZW-ROUTER
Buffer memory	up to 95k measurements	5k measurements	4k measurements	3k measurements				N/A
Measurements	N/A	Temp	Temp/RH	Ext T/RH, 1 analog port 1 pulse input port	4 external analog ports	Ext T/RH, 2 analog ports	2 analog ports 2 pulse input ports	N/A
Probe size	N/A	N/A	N/A	1cm (0.38 in) dia.	N/A	1cm (0.38 in) dia.	N/A	N/A
Sample rate	N/A	1 min to 18 hrs	1 min to 18 hrs	1 min to 18 hrs	1 min to 18 hrs	1 min to 18 hrs	1 min to 18 hrs	N/A
Transmission rate	N/A	2 min & greater	2 min & greater	2 min & greater	N/A	2 min & greater	2 min & greater	N/A
Power options (included)	AC adapter, Battery Backup, USB power	AC Power Adapter, Battery Backup						
Measurement range	N/A	Temp: -20° to 70°C (-4° to 158°F)	Temp: -20° to 70°C (-4° to 158°F) RH: 5 to 95% RH	Temp: -20° to 70°C (-4° to 158°F) RH: 5 to 95% RH Analog: o to 2.5 VDC Pulse: 0 to 65,535 pulses per logging interval	Analog channels: 0 to 2.5 VDC; 0 to 5 VDC	Temp: -20° to 70°C (-4° to 158°F) RH: 5 to 95% RH	Analog channels: 0 to 2.5 VDC; 0 to 5 VDC	N/A
Accuracy	N/A	Temp: ± 0.21°C from 0° to 50°C (± 0.38°F from 32° to 122°F)	Temp: ± 0.21°C from 0° to 50°C (± 0.38°F from 32° to 122°F) RH: ± 2.5%	Temp: ± 0.21°C from 0° to 50° C (± 0.38°F from 32° to 122°F) RH: ± 2.5% Analog: ± 1.544 mV + 2%	Analog: ±1.544 mV plus 2% of reading	Temp: ± 0.21°C from 0° to 50°C (± 0.38°F from 32° to 122°F) RH: ± 2.5% Analog: ± 1.544 mV + 2%	Analog: ± 1.544 mV plus 2% of reading	N/A
Resolution	N/A	Temp: 0.02°C @ 25°C (0.04°F @ 77°F)	Temp: 0.02°C @ 25°C (0.04°F @77°F) RH: 0.03%	Temp: 0.02°C @ 25° C (0.04°F @77° F) RH: 0.03% Analog channel: 0.6 mV Pulse Channel: 1 pulse	Analog channel: 0.6 mV	Temp: 0.02°C @ 25°C (0.04°F @77°F) RH: 0.03% Analog channel: 0.6 mV	Analog channel: 0.6 mV Pulse Channel: 1 pulse	N/A
Range	Approx. 100 m (300 ft.) depending on obstructions or interference							
Dimensions	96.5 x 108 x 28 mm (3.8 x 4.25x 1.1 in)							
CE compliant	Yes							

Contact Us

Sales (8am to 5pm ET, Monday through Friday)
- Email sales@onsetcomp.com
- Call 1-508-759-9500
- In U.S. toll free 1-800-564-4377
- Fax 1-508-759-9100

Technical Support (8am to 8pm ET, Monday through Friday)
- Contact Product Support onsetcomp.com/support/contact
- Call 1-508-759-9500
- In U.S. toll free 1-877-564-4377

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Bourne, MA 02532

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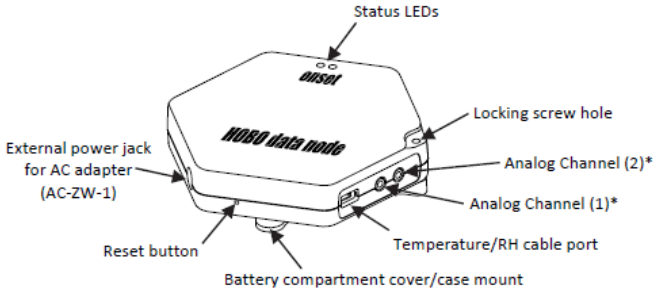
HOBO® Data Node, Ext Temp/RH, 2 Analog (ZW-007)

The HOBO ZW-007 data node is configured with a temperature/RH channel designed to accept the included temperature/RH cable, along with two analog channels. The analog channels accept a wide range of Onset and third-party sensors/transducers with 0–2.5 VDC output, including temperature and AC current sensors. Specifications for Onset sensors are available at onsetcomp.com or from an Onset Authorized Dealer. For 0–5 VDC, 0–10 VDC, or 4–20 mA output, use optional Onset part numbers CABLE-ADAP5, CABLE-ADAP10, or CABLE 4-20 mA respectively.

This node has routing capability in the ZW wireless network when initially powered with an AC adapter. Refer to the *HOBO ZW Series Wireless Network Quick Start Guide* for information on how to set up this node.



***Caution:** Analog channel input cannot exceed 2.5 VDC. For sensor outputs up to 10 VDC, use appropriate voltage adapter cable.

HOBO Data Node (ZW-007)

Included Items:

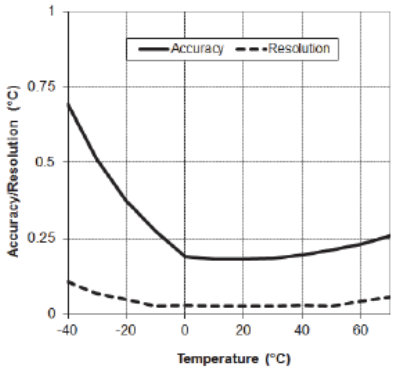
- AC adapter (AC-ZW-1)
- Temp/RH cable
- 3 AAA batteries
- 1 locking screw
- Hook & loop tape
- Adhesive label
- Bracket kit (ZW-BRACKET)

Specifications

Radio power	1.6 mW (2 dBm)
Transmission range	Approx. 100 m (328 ft), depending on obstructions or interference
Wireless data standard	IEEE 802.15.4, 2.4 GHz band
Measurement ranges	Temperature: -40° to 70°C (-40° to 158°F) RH: 0% to 100% RH, -40° to 70°C (-40° to 158°F) Analog channel: 0 to 2.5 VDC, 0 to 5 VDC (with CABLE-ADAP5), 0 to 10 VDC (with CABLE-ADAP10), 4-20mA (with CABLE-4-20mA)
Accuracy	Temperature: ±0.21°C from 0 to 50°C (±0.38°F from 32° to 122°F) RH: ± 2.5% from 10 to 90% typical to a maximum of ±3.5% including hysteresis at 25°C (77°F); below 10% and above 90% ±5% typical Analog channel: ± 1.544 mV plus 2% of reading typical
Resolution	Temperature: 0.02°C at 25°C (0.04°F at 77°F) RH: 0.05% Analog channel: 0.6 mV
Response time	Temperature: 5 minutes in air moving 1 m/sec (3.3 ft/sec) RH: 10 minutes in air moving 1 m/sec (3.3 ft/sec) with protective cap
Operating temperature	-20° to 50°C (-4° to 122°F), when battery powered, -20° to 70°C (-4° to 158°F) when line powered
Stability (drift)	Temperature: < 0.1°C (0.18°F) per year RH: <1% per year typical
Operating RH	5% to 95% non-condensing
Time accuracy	± 1 minute per month at 25°C (77°F)
Memory capacity	128K
Power options	Data mode: battery powered (3 AAA alkaline batteries); 1-year battery life at 15-minute logging interval Data/router mode: AC power adapter (input: 100–240 V at 50/60 Hz 0.20 A output: 6 VDC at 0.5 A), batteries as backup power

Specifications (continued)

Case material	ABS
Dimensions	96.5 x 108 x 28 mm (3.8 x 4.25 x 1.1 in.)
Weight (with batteries)	138 g (4.87 oz)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).
FC	See below



Plot A

FCC Compliance

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one of the following measures:

- Reorient or relocate the receiving antenna
- Increase the separation between the equipment and receiver
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected
- Consult the dealer or an experienced radio/TV technician for help

Changes or modifications not expressly approved by Onset Computer Corporation could void the user's authority to operate the equipment.

To comply with FCC and Industry Canada RF radiation exposure limits for general population, the HOBO data nodes, receivers, and routers must be installed to provide a separation distance of at least 20cm from all persons and must not be co-located or operating in conjunction with any other antenna or transmitter.

Canada

This device has been designed to operate with the antenna listed below, and having a maximum gain of 1 dB. Antennas not included in this list or having a gain greater than 1 dB are strictly prohibited for use with this device. The required antenna impedance is 50 ohms.

To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that permitted for successful communication.

Approved antenna: Johanson Technologies P/N 2450AT45A100 1.0 dBi chip antenna

FCC Declaration of Conformity

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

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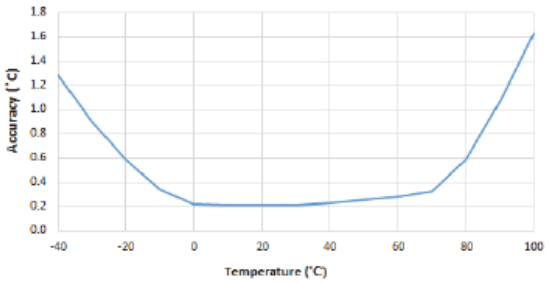
TMCx-HD Water/Soil Temperature Sensor

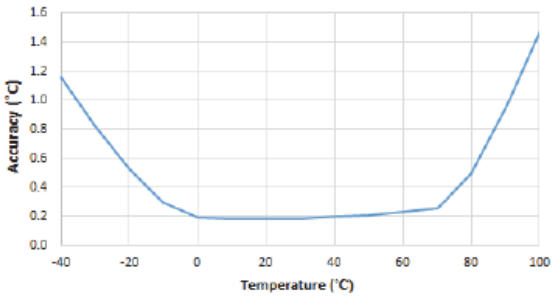
For use with HOBO® U12 and UX120-006M data loggers and ZW data nodes

Specifications

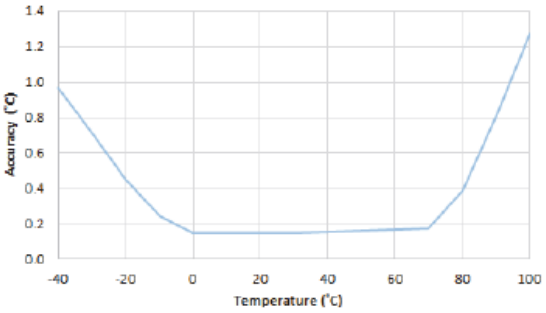
Measurement Range	-40° to 50°C (-40° to 122°F) in water; -40° to 100°C (-40° to 212°F) in air
Accuracy with U12	±0.25°C from 0° to 50°C (±0.45°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot A
Accuracy with ZW	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot B
Accuracy with UX120-006M	±0.15°C from 0° to 50°C (±0.27°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot C
Resolution with U12	0.03° at 20°C (0.05° at 68°F)
Resolution with ZW	0.02°C at 25°C (0.04°F at 77°F)
Resolution with UX120-006M	0.002° at 25°C (0.003° at 77°F)
Drift	<0.1°C (<0.2°F) per year
Response time in air	2 min. typical to 90% in air moving 1 m/sec (2.2 mph)
Response time in stirred water	30 sec. typical to 90%.
Operating range	Sensor tip and cable immersion in fresh water up to +50°C (122°F) for 1 year
Housing	Copper-plated sensor tip
Dimensions	5.1 x 33 mm (0.2 x 1.3 inches)
Weight	34 g (1.1 oz)



Plot A: U12 Accuracy*



Plot B: ZW Accuracy*



Plot C: UX120-006M Accuracy*

*Accuracy shown in plots outside the 0 to 50°C range is typical.

Mounting Considerations:

- Mount the sensor where there is good air circulation for measuring air temperature.
- Mount the sensor off the mounting surface so temperature measurements are not affected by the surface itself.

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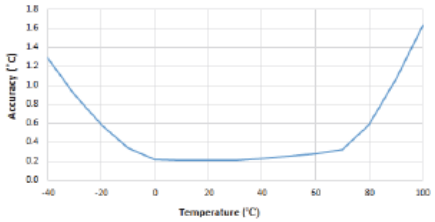
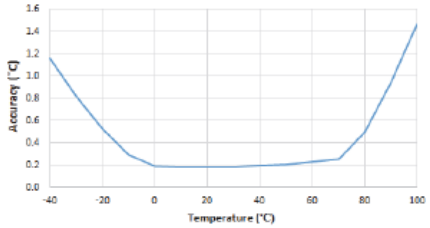
For use with HOBO® U12 and UX120-006M data loggers and ZW data nodes

Specifications

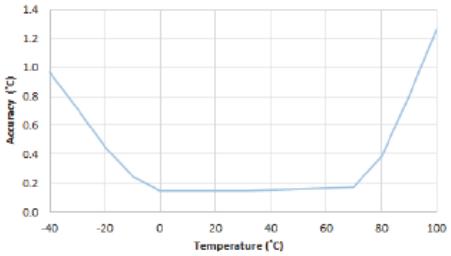
Measurement Range	-40° to 100°C (-40° to 212°F)
Accuracy with U12	±0.25°C from 0° to 50°C (±0.45°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot A
Accuracy with ZW	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot B
Accuracy with UX120-006M	±0.15°C from 0° to 50°C (±0.27°F from 32° to 122°F), insert probe 2.3 cm (0.9 inches) minimum; see Plot C
Resolution with U12	0.03° at 20°C (0.05° at 68°F)
Resolution with ZW	0.02°C at 25°C (0.04°F at 77°F)
Resolution with UX120-006M	0.002° at 25°C (0.003° at 77°F)
Drift	<0.1°C (<0.2°F) per year
Response time in air	2 min. typical to 90% in air moving 1 m/sec (2.2 mph)
Response time on a pipe	Typically 2 times faster than the TMCX-HD. Typically less than 1 minute to 90%.
Housing	Copper-plated sensor tip
Dimensions	0.9 x 5.8 cm (0.38 x 2.30 inches)
Weight	34 g (1.1 oz)



Plot A: U12 Accuracy*



Plot B: ZW Accuracy*



Plot C: UX120-006M Accuracy*

*Accuracy shown in plots outside the 0 to 50°C range is typical.

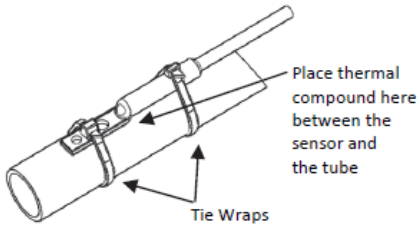
Items Included:

- 2 tie wraps
- 1 #6 screw
- Thermal compound

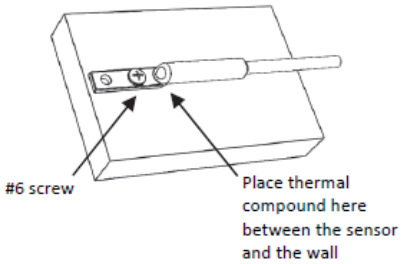
Mounting the Sensor

Use a small amount of the enclosed thermal compound between the flat part of the sensor tip and the surface where the sensor is being deployed to enhance the contact between the two.

Sensor mounted on pipe using two tie wraps:



Sensor mounted on wall using #6 screw:



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9.6 Appendix F – Timer Specifications

PRODUCT DIMENSIONS

- 3.8" L x 1.4" H x 2.4" D

WEIGHT

- 3.2 ounces

SYSTEM REQUIREMENTS

- Wi-Fi router
- Android 4.4 or higher
- iOS 9 or higher

GENERAL SPECIFICATIONS

- Electrical Rating: 120V~/15A/60Hz/1800W
- Wi-Fi: 2.4GHz 801.11n

9.7 Appendix G – Temperature Controller Specifications

WH1436 Temperature controller

Specification:

- Power supply: AC 110V ~ 240V, 50/60Hz
- Measure range: -20 ~ 105 C (-4 ~ 221 F)
- Temperature resolution: 0.1
- Accuracy: ±0.1
- Working mode: Heating /Cooling mode
- Control resolution: 0.1
- Power consumption: less than 3W
- Relay contact capacity: 8A

9.8 Appendix H – Detailed Specifications of PCM

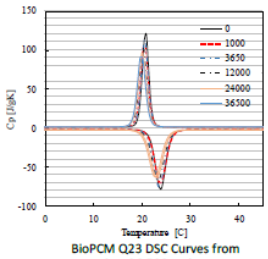
PHASECHANGE
ENERGY SOLUTIONS

ENRG Blanket™ Technical Data

ENRG Blanket is powered by Phase Change Energy Solutions' proprietary phase change material, BioPCM®. BioPCM absorbs and releases significant thermal energy at a specific design temperature to provide maximum energy performance to match needs and requirements of building owners.

ENRG Blanket Features:

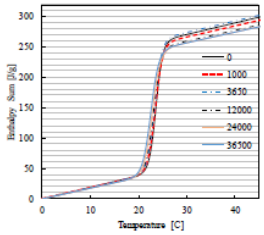
- Made from all natural, food grade vegetable oils
- Formulated and tested for long life, > 100 years
- Tunable congruent melting and freezing temperature
- Non-Toxic
- 100% Recyclable and biodegradable
- Contractor friendly installation ready design
- Available in multiple fire classes, including Zero Smoke/Zero Flame plenum



BioPCM Q23 DSC Curves from 0 to 36,500 cycles:

ENRG Blanket Q23/M27 Technical Characteristics

BioPCM:	Proprietary blend of emulsifiers, gelling agents, fatty acids and their derivatives	
Encapsulation:	14 mil multilayer white polyfilm	
M-Value:	27 BTU per sq. ft. latent heat storage, per ASTM test	
Melting Point:	73.4° Fahrenheit	23° Celsius
Specific Heat:	0.9-1.1 BTU/pound	
Latent Heat:	~92.4 BTU/pound	
Weight:	.51 pounds per sq. ft.	



BioPCM Q23 Enthalpy Curves from 0 to 36,500 cycles:

Flame Spread Ratings

ENRG Blanket is available in multiple flame spread rate classes to meet the requirements of the ASTM E84, UL 723 and ASTM E800-0.

- Plenum: Flame Spread 0-25; smoke-developed 0-50
- Class A: Flame Spread 0-25; smoke-developed 0-450
- Class C: Flame Spread 76-200; smoke-developed 0-450

Manufactured By
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